Realtime communications for the distributed control of energy systems

A CONFIRMATION OF CANDIDATURE REPORT SUBMITTED TO

THE SCIENCE AND ENGINEERING FACULTY

OF QUEENSLAND UNIVERSITY OF TECHNOLOGY

IN FULFILMENT OF THE REQUIREMENTS FOR THE CONFIRMATION OF CANDIDATURE OF

DOCTOR OF PHILOSOPHY

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March 2017

Abstract

When it comes to selling electricity back to the grid prosumers who have invested in renewable electricity generation sources like solar panels face two main constraints, unfavourable pricing and access to affordable associated battery storage systems. One solution to the first problem is for the regulating authorities to set better feed in tariffs. This research proposes an alternative solution, a real-time market based energy bidding and trading between aggregators and prosumers. Instead of prosumers interacting directing with energy companies this research proposes the use aggregators who act as contract brokers between energy companies and prosumers. A framework is proposed that includes appropriate network protocols, network services, a suitable network architecture, a messaging system, applications and algorithms to allow energy bidding and trading between aggregators and prosumers. The research significance is substantial original contribution towards further reduction in greenhouse emissions by having a system that allows more renewable energy source participants in electricity generation.

Index Terms – Distributed Battery Storage Systems, BESS, Smart grid, Real-time energy trading, Energy Bidding, BESS, Distributed Energy Resources (DER), Real-time protocols

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Chapter 1

Statement of Research Problem

1.1 Background

One way of lowering greenhouse gas emissions is by reducing the use of fossil fuels for electricity generation. Incorporating renewable electricity generation sources like solar and wind into the electricity grid is one way of doing that. To incentivize more users to invest in renewable generation whilst offsetting the intermittent nature of renewable energy sources, two things are essential, energy storage and trading. As energy storage technology and manufacturing processes mature, battery energy storage systems (BESSs) will become more affordable and more efficient. This means in the smart grids of the future a majority of individual homes and companies will be able to store excess energy generated from renewable sources like solar and wind, and sell it back to the electricity companies any time during the day, not just when the sun is up or wind is available.

When it comes to selling energy back to the grid most energy consumers and producers (*prosumers*) are constrained by two main things. Firstly, due to the lack of battery energy storage systems they can only sell when there is sunlight or wind for example. This is not ideal for them or the energy companies.

The second issue is that of pricing. They can only sell to the utility company providing them with the electricity that also sets the pricing for them. For example in Queensland if your electricity provider is Origin you can only sell back to them at a set feed-in tarriff. Ideally *prosumers* would want a market based energy bidding and trading process involving several aggregators and utility companies to get a competitive price than the feed in tarriff.

This research will look at ways of facilitating real-time energy trading between *prosumers* and electricity aggregators, and to create a framework for such a system. Detailed requirement analysis will be conducted. Associated messaging systems, energy trading algorithms, network architecture and protocols will be investigated, designed and developed. Models and simulations will be used to demonstrate this framework. The end result should be a system that allows an increased financial reward for *prosumers* as well as an increase in the amount of energy sources in the smart grid as more *prosumers* have a financial incentive to sell energy to the grid. This is especially important during periods of peak demand like a heatwave or a cold winter night.

1.2 Research Problem

To encourage and accelerate the adoption of renewable electricity generation by *prosumers* we need a real-time market-based energy system between distributed battery energy storage systems (D-BESS) and electricity aggregators. Currently there are somewhat similar systems as discussed in the literature like microgrid to microgrid energy bidding and trading but as far as this researcher is aware there is none that facilitate trading between D-BESSs and aggregators. In such a system energy bidding and trading messages will have to be exchanged in real-time. The messages exchanged need to consist of such information as total stored energy in a battery energy storage system (BESS), what percentage of it is available for sell, real-time pricing and bidding.

By knowing how much energy (in kWh) a BESS has and what percentage of it is available for sale, an aggregator might decide whether to bid or not for that energy. Messages can be used to join a trading group, make bids, accept bids, ejects bids and make offers (cents/KWh) for example. The essential part of the messaging system is that they need to be exchanged in real-time.

This thesis seeks to investigate and develop such a system. The appropriate network architecture, network services, network protocols, messages, real-time requirements and bidding algorithms for such a system will be investigated.

1.3 Research Question

Following the discussion of the research problem in section 1.2 the main research question becomes “What framework can facilitate the implementation of a market based energy trading between D-BESS and aggregators in real-time?”. The research question is further split into three sub questions.

1. What is the suitable network architecture?
2. What protocols should be developed at an ISO (International Organization for Standardization) layer identified for this type of application?
3. What application layer network services and messages should we have?

1.4 Aim and Objectives

The primary aim of this research is to investigate a solution for the research problem as described in 1.2 and this is achieved by meeting three objectives. The objectives are to answer the research questions defined in 1.3. The three objectives are to investigate a suitable data communications architecture, investigate and develop a suitable protocol suite and finally to investigate application layer network services and messages.

1.4.1 Investigate a suitable data communication architecture(s)

Research into smart grid data communications architectures will be undertaken with the aim of coming up with a suitable architecture for real-time communications for distributed control of energy systems. Issues to consider include whether a wired or wireless medium can be used. Depending on the results of bandwith and latency analysis a wireless technology like 3G or LTE might be sufficient or a wired solution like xDSL or optic fibre might be required.

1.4.2 Investigate and develop a protocol suite

Research will need to be taken into protocol design and implementation. Investigation will be undertaken into which layers of the OSI model are best suited for the required protocol suite.

Real-time parameters will need to be defined. For example, how much delay in milliseconds is acceptable for each type of message and what are the ramifications of too much delay.

1.4.3 Investigate and develop application layer network services

The type of network services, applications and messages will be investigated. There are messages to query the total energy energy available in a battery energy storage system and what percentage of it is available sale for example. Investigation into congestion control and message prioritisation will be undertaken here so are message formats and lengths. Type of messages that need to be exchanged in real time will also need to be determined.

1.5 Research scope

The smart grid consists of the electricity network and the data communications network. The main focus of this research is the real-time data communications requirements for the distributed control of energy systems in the smart grid. How the BESSs are electrically integrated into the smart grid electricity network is beyond the scope of this research. The research outcomes are envisioned to be fully realised in the future (probably by the time this research is finished as BESS prices continue to drop) when the majority of *prosumers* own BESSs and there a substantial number of aggregators.

Chapter 2

Literature Review

2.1 Introduction

In line with the research objective, research question and sub-questions outlined in the introduction (Chapter 1), distributed renewable energy systems (DRES) will initially be reviewed. This will be followed by looking at current methods of energy trading the smart grid. Finally, I will review the necessary communications infrastructure necessary for real-time communications for distributed control of energy systems. I will review the IEC (International Electrotechnical Commission) 61850 communication standard, the object-oriented data model, real-time communications using Manufacturing Message Specification (MMS) and Generic Object Oriented Substation Event (GOOSE) and a review of suitable network architectures with particular emphasis on wireless technologies.

2.2 Distributed Renewable Energy Systems (DRES)

There is going to be a substantial shift from large scale power plants towards a large number of distributed renewable energy sources. Distributed renewable energy systems generate clean electricity at the site where the energy will be used as opposed to remote generation at centralised power plants. There are many benefits of distributed energy systems. There are many benefits of distributed energy systems. According to Bayram et al. [2014] these include include improved efficiency of grid operations, minimisation of operational costs and reduction of greenhouse gas emissions. I think government incentives like the Queensland government solar bonus scheme also play a major role. The affordability Chen et al. [2009] and availability of electrical energy storage units is also helping towards the push for distributed energy systems in the smart grid. From a consumer point of view, I believe there is an opportunity to not only to sell excess energy back to the electric grid but also to get the best price as multiple aggregators and utilities participate in the distributed energy system thereby recovering investment costs sooner and make a profit.

2.3 The role of aggregators

In the smart grid an aggregator is a broker or intermediary between customers and electricity suppliers. "An aggregator is an entity which collects power generated from microgrids and resells it to the utility." Kim and Thottan [2011].

In their paper "A Two-Stage Market Model for Microgrid" Kim and Thottan [2011], they describe a two-stage model that illustrates the role of aggregators in microgrid transactions. They describe how aggregators can mitigate the sudden demand for electricity during peak periods by quickly supplying power to the main grid since they have access to a large of various energy sources like battery storage units and renewable sources like solar and wind.

Kim and Thottans paper describes a method utility companies and microgrids using aggregators they fall short of addressing the requirement of this thesis which is to facilitate energy bidding and pricing between *prosumers* and aggregators. It is my suggestion that, their framework and equations can be adapted to form a basis for market based energy trading between home users and aggregators.

From the time the electricity market was deregulated around the world in order to create competition several challenging problems associated with maintaining a reliable and economical power supply have been identified Nguyen et al. [2013] and DR (demand response) is one of the solutions. One way of reducing electricity demand during peak periods is by using DR systems. A DR system provides a way for consumers to actively participate in the smart grid reducing their power usage during peak periods. Real-time communications in the smart grid is one of the key DR enablers. Aggregators can play a significant role in DR systems Gkatzikis et al. [2013] and I believe aggregator based DR systems in conjunction with market based energy trading between consumers and aggregators is an effective way of reducing greenhouse based electricity generation whilst at the same time rewarding consumers for investing in renewable sources electricity generation.

2.4 Energy trading in the smart grid

2.4.1 Market-based energy trading

A market-based energy pricing system is a competition based system. For the purposes of this thesis it is competition between aggregators, competing for the energy in *prosumers'* battery energy storage systems (BESS). There are several methods for energy trading in the smart grid. For example, Wang and Huang Wang and Huang [2015] have modelled energy trading between autonomous microgrids for their mutual benefits. They have designed a bargain-based energy trading systems that is based on Nash's model of bargaining.

Energy pricing in the smart grid is very complicated. It is complicated for both the resellers and the consumers. As Kim et al. [2016] have pointed out, it is difficult for resellers because of the lack of information from the customer side. Customers face the uncertainty of retail electricity pricing. Implementing a market-based trading system is even more complicated. To overcome these challenges Kim and the team use reinforcement learning.

2.4.2 Nash equilibrium in energy trading

When a system is in Nash equilibrium, a stable state, no participant can gain by unilaterally changing the game strategy if the others' strategies remain unchanged. The objective of the *prosumers* is to maximize the amount of money they can get per kWh from the aggregators whilst competing among themselves. In an energy trading system with a Nash equilibrium , no *prosumer* will financially benefit by changing the pricing strategy.

Wang et al. [2014] formulated a game between non-cooperative BESSs that were trading their stored energy and demonstrated the existence of at least one Nash equilibrium. In this case I don't think some *prosumers* would want to be in a Nash equilibrium as it doesn't guarantee the optimum outcome (best price). This is because Nash equilibrium doesn't take the risk element into account. For example a *prosumer* might want to set a sale price significantly higher than others. The drawback is that no aggregator might be willing to pay that price but the reward is better sale price than everyone else. This is because aggregators might not use the price per kWh alone as a deciding factor in buying energy, they might consider the total amount of energy available or trading history (is the BESS reliable). Since finding Nash equilibrium is computationally expensive Daskalakis et al. [2009] it is an issue in a large scale energy trading system with thousands of BESSs. A positive consequence of Nash equilibrium is the result in the enhancement of a power system reliability and robustness Wang et al. [2014] as well as price stability.

2.4.3 Virtual Power Plant (VPP) energy trading

A virtual power plant (VPP) is an aggregation of different power sources (BESSs, solar, wind, small hydro, etc.) that act as a single power plant Gong et al. [2011]. Because of the flexibility of the VPP Petersen et al. [2013] looked at how the principals of marginal and fixed costs apply to a VPP operation in order to see how much profit can be made in a VPP after trading flexibility. Day-ahead, intra-day and regulating power markets were included in their model to test and confirm the assumption that a VPP can make extra profit by being a participant in multiple markets.

For the VPP, one approach to energy bidding that considers inter-temporal effects is price-based unit commitment (PBUC) Peik-herfeh et al. [2014]. To mitigate the effects of the stochastic nature of some distributed generation (DG) sources and how market price forecasting can directly influence the PBUC approach to energy trading, Peik-herfeh et al. [2014] proposes a two-stage dispatch framework. Optimal bidding is dealt with in the first stage whilst the second stage deals with active distribution network management (ADNM). Distribution system operator (DSO) operation costs can be reduced by the ADNM whose function is also to update each distributed energy resourse's (DER) optimal bid after determining its power generation capacity.

A different VPP energy strategy proposed by Mnatsakanyan and Kennedy [2013] involve the combination of demand response (DR) and distributed generators (DR) into a single energy profile. Inside the VPP there are individual DR contracts with consumers that allow the VPP to buy reductions optimally. The surplus energy is then sold on the wholesale market.

2.4.4 Electric vehicle (EV) energy trading

Although the initial objectives of deploying electric vehicles (EVs) were environmental it has since been realised that they are also a source of energy. This is especially true during periods of peak electricity demand and emergencies. There are several methods of energy trading between EVs and the smart grid. Nguyen and Le [2014] demonstrated that a smart grid can increase its profits by creatively cordinating renewable energy genation with electric vehicle charging.

Unlike previous works where the obvjectives are for the sellers to maximize profit and for the buyers to pay as little as possible, Kim et al. [2013] consider an approach where the users care about the welfare of the power system. Their scheduling algorithm takes advantage of the charging and discharging nature of EVs. By considering their electricity bills and the power usage from their other household appliances, *prosumers* determine how much energy to sell to the aggregators.

2.4.5 Day-ahead and machine learning based energy trading

In a day-ahead electricity market sellers and buyers make contracts for the delivery of electricity the next day, they agree on a fixed price the day before the actual electricity is delivered.

Machine learning techniques can be used to determine prices in energy trading. Using a recursive neural network (RNN) technique Mandal et al. [2007] devised a method for predicting prices in the day-ahead electricity trading market on an hourly basis. Dehghanpour et al. [2016] used Dynamic Bayesian Network (DBN) representation as basis for an agent-based optimal bidding tool. Fan et al. [2006] takes a different approach to day-ahead price forecasting by utilising Support Vector Machines (SVM) in addition to Bayesian Clustering by Dynamics (BCD) as the machine learning techniques. They demonstrated that this method can predict spot prices with a very high degree of accuracy.

I believe that as Big Data becomes more prevalent and machine learning techniques evolve, the future of energy trading and bidding will be mostly machine learning based.

2.5 Distributed communications architecture (DCA)

Because a single network architecture does not always suite the data communications requirements of the smart grid, a distributed communications architecture is therefore essential. A distributed network spans different networks. Just like in other distributed paradigms like distributed computing, distributed control or distributed algorithms the main objective is scalability and for the system to appear as a single entity to the user.

2.6 Real-time Communications for distributed control of energy systems

In a distributed energy storage control system, the storage and control elements are decentralised. At the heart of any distributed system is the communication and coordination of actions by message passing. The control elements are distributed throughout the system and are connected via wired or wireless networks and have the ability to talk to each other using protocols based on the IEC 61850 standard. In microgrids a decentralized approach to energy storage control "allows a very flexible system that can adapt to changing system structures and situations" Weaver et al. [2015].

Due to the discontinuous nature of renewable energy resources energy storage is essential in providing a flexible and reliable grid system. Power is usually generated somewhere and consumption is in major population centres that can be hundreds or thousands of kilometres away. The integration of renewable sources of energy in the form of distributed generation (DG) into the grid and microgrids is growing rapidly Molina [2012].

All these factors make it essential to have an effective distributed energy storage system. The importance of a distributed energy system is that it appears to the user as a single entity. Energy storage also mitigates renewable energy sources like solar and wind intermittency. Renewable energy generation systems can form part of a distributed control system in the smart grid by having "an electrical grid divided into several control areas, distributed renewable energy generation systems, distributed control systems and a real-time communication network" Qi et al. [2011]. Halvgaard and colleagues Halvgaard et al. [2016] consider Douglas-Rachford splitting as a method for solving real-time control of a large number of units in a distributed energy system. What is clear is that for distributed renewable energy systems to be effective in the smart grid is the need for real-time communications regardless of the approach or method employed for the control of these systems. The essential factor in having a reliable electricity delivery in the smart grid is by having information that is both reliable and delivered in real-time Gungor et al. [2011]. As noted by Dehalwar and colleagues Dehalwar et al. [2015] ***real-time communications*** in the smart grid is very challenging due to its sheer size and associated complexities. Several methods and protocols of which IEC 61850 is amongst them have already been drafted to tackle real-time communications challenges in the smart grid.

2.6.1 IEC 61850 communication standard overview

There are many technologies currently in use in the smart grid with several being in the developmental phase Gungor et al. [2011]. This results in the lack of a widely accepted standard thereby undermining the rapid development of the smart grid. One standard that is gaining standard is the IEC 61850 standard. The IEC 61850 standard outlines a framework for communication between several single devices in the power system. The standard was designed to separate the data model from method of communication. It was also designed to address the importance of a structured approach to the design of substation automation systems, utilise existing technologies like Ethernet and TCP/IP, simplify system configuration, device measurement sharing and to enable vendor independence. Although the scope of the IEC 61850 standard was originally substation-to-substation focussed its abstract model make it intuitive to develop smart grid applications that extend beyond the substation boundary like a market based energy trading system for example.

When it comes to incorporating distributed energy resources (DERs) into the smart grid I see the IEC 61850 standard as the most appropriate to use. This is mainly because of its flexibility. The flexibility to lies in the ability to adopt it to wind farms or solar for example, as each DER has its own set of requirements. The penalty of flexibility is that it can result in complexity.

The standard defines 10 major sections and a total of 13 logical group nodes Kostic et al. [2005]. IEC 61850 takes advantage of an object oriented data model that facilitates mapping to a number of protocols that utilise existing TCP/IP networks or fast Ethernet. These protocols include GOOSE (Generic Object Oriented Substation Event), MMS (Manufacturing Message Specification), SMV (Selectable Mode Vocoder) Grids and Elmusrati [2013] and more recently DPWS (Devices Profile for Web Services).

2.6.2 The object-oriented data model

The IEC 61850 is at the heart of data communications in the smart grid. The IEC 61850 is an abstract application layer protocol Ozansoy et al. [2009]. It abstracts the definition of data items and services. This allows the mapping of data objects (commonly referred to as Logical Nodes) "and services to any other protocol, which provides adequate communication procedures meeting the data and service requirements of the IEC 61850 standard" Ozansoy et al. [2009]. The basic data model structure is application independent. Data items or objects are independent of the underlying protocols. The main advantage of the IEC 61850 modelling approach is that it provides a model of how IEDs (Intelligent Electronic Devices) should organise data in a consistent manner across device brands. The most important point to note is that devices can configure themselves and client applications can extract object definitions over the network resulting in time (no need to manually configure devices) and cost savings. This is crucial in distributed control of energy systems that adhere to the IEC 61850 standard. I believe that this object-oriented approach to data modelling facilitates rapid and intuitive applications and frameworks that enhances the smart grid.

2.6.3 Real-time communications using Generic Object Oriented Substation Event (GOOSE)

The IEC 61850 allow peer-to-peer communication model for Generic Substation Events (GSE) between Intelligent Electronic Devices (IEDs) in a substation. A Generic Object Oriented Event (GOOSE) message is one of the messages associated with a GSE Kriger et al. [2013]. GOOSE messages are mapped directly on the data-link layer resulting in low delay in the network. Time-critical events are usually multicast across a local Ethernet network as GOOSE messages. The importance of GOOSE is that it helps to satisfy the real-time requirements of the smart grid inside a local area network (LAN). GOOSE messages cannot travel beyond the local area network since GOOSE does not have a Network (Layer 3) component. This is to be taken into account when designing a real-time communications system for the distributed control of energy systems.

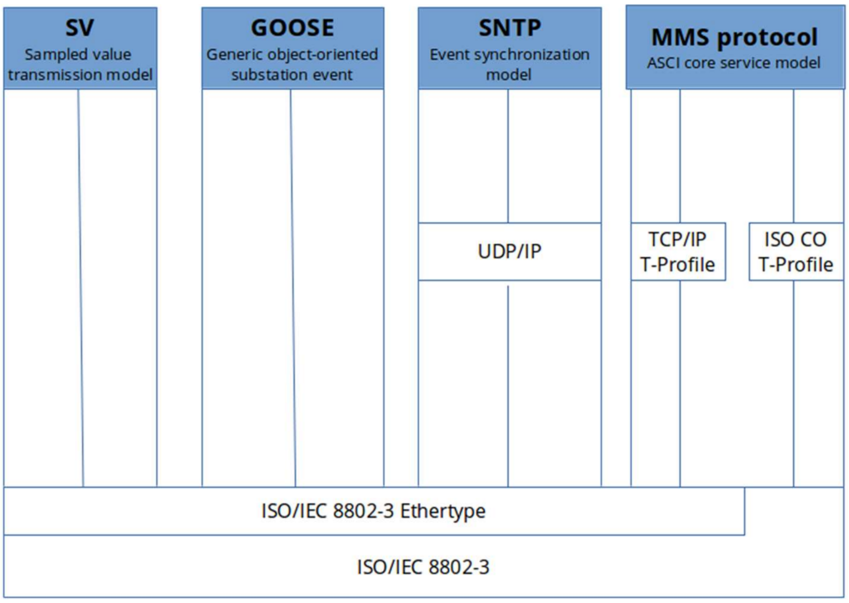

Figure 2.1: Communication stacks of IEC 61850

2.6.4 Real-time communications using Manufacturing Message Specification (MMS)

The Manufacturing Message Specification (MMS) is vendor-neutral international standard that deals with processing data in real-time. This is in addition to facilitating the transfer of supervisory information transfer between intelligent electronic devices (IEDs) and systems. MMS defines a set of standard objects that must be in every device on which operations like read and write can be executed, a set of standard messages for monitoring and control between clients and servers and finally a set of encoding rules for mapping these messages to bits and bytes when transmitted. The abstract communication service interface (ACSI) definition is at the core of IEC 61850. MMS is one (others include Web Services) of the mappings implementing these services. As previously discussed GOOSE messages are limited to communications within a LAN (local Area Network) due to lack of Layer 3 information so when we want support for transfer of real-time process data and supervisory information over a WAN (Wide Area Network) we can use MMS as it resides on top of the TC/IP stack as shown in 2.1.

2.7 Network architecture for real-time communications of distributed energy systems

As observed by Abdrabou [2016] the conventional power grid was not designed with distributed renewable energy sources in mind. As a consequence, distribution network operators (DNOs) have to consider the bidirectional flow of both the power and communications systems. As a result, active management and decentralised control are unavoidable Abdrabou [2016].

In their paper Hammoudeh et al. [2013] discuss five possible network architectures for the smart grid as being direct connect, local access aggregators, interconnected local access aggregators, mesh and Internet cloud. They correctly suggest that a single architecture is not suitable for every scenario.

Optic fibre and twisted pair communications transmission media in the smart grid are well understood and documented. In this section I briefly discuss wireless communications for the smart grid mainly because wired architectures might not be cheaply available if available at all. This is especially true for remote locations here in Australia. The proliferation of wireless broadband access is one of the catalyst for the success of smart grid deployments Budka et al. [2010]. There are several wireless communications technologies that can be used in the smart grid depending on the application. They include Wi-Fi (IEE 802.11), LTE (Long-Term Evolution, also known as 4G), HSPA+, UMTS (Universal Mobile Telecommunications System, also known as 3G), EDGE and WiMAX. Factors to that influences choices include latency, bandwidth, cost of deployment and coverage. Wireless technologies also have other challenges that include reliability, availability and high voltage electromagnetic interference Parikh et al. [2010]. In the paper Abdrabou [2016], Abdrabou introduces a low cost and efficient wireless communications architecture based on a multichannel wireless mesh which is a typical cellular structure. Since Abdrabou suggests using several wireless channels as an essential element in his design I dont agree with his assertion that this is a simple design. I believe it actually introduces multiple levels of complexity.

Quality of Service (QoS) in smart grid communications: QoS is a whole set of technologies aimed at prioritising some traffic ahead of others. In bandwidth constrained environments real-time traffic can be given a higher priority in smart communications using QoS.

Other promising wireless technologies are LTE and WiMAX. LTE is a high-speed wireless communication standard. Studies have already been conducted on the feasibility of using LTE in smart grid network architectures Patel et al. [2016]. Its low latency, high throughput and QoS differentiation are highly attractive to the real-time requirements of the smart grid Patel et al. [2016]. In their paper, Patel and team suggests using LTE coupled with QoS for MMS (manufacturing messaging specification) for smart grid applications Patel et al. [2016]. Their proof of concept concluded that LTE can be used for real-time communications in the smart grid.

In another investigation Awad et al. [2015] also demonstrated how QoS can be used in LTE networks to ensure real-time packet delivery. As major telecommunications organisations in Australia continue to invest in LTE, LTE will play a major role in smart grid applications like energy trading systems.

2.8 Power line communications (PLC)

One of the components of the smart grid makes it smart is the data communications aspect of it. Power line communications (PLC) is one of the promising technologies to enable it. Power line communications is a data communications technology that use existing power power cables as a transmission media.

There are several problems with PLC, they include background noise and impedance mismatch Kim et al. [2011] resulting in a multipath problem and delay spread. Several methods have been suggested to overcome these limitations

I see PLC being widely adopted in the future for data communications for the distributed control of energy systems mainly because of the ease of deployment (where there will be power lines there will be data communications) and cost savings that can be realised.

2.9 Knowledge gap

As seen from the literature energy trading in the smart grid can be too complex or too general. For examples techniques like day ahead energy trading and bidding can be too risky and inflexible. Others like Wang et al. [2017] have proposed risk constrained approaches, they are still in their infancy, however anyone should be able to incorporate that techniques in this research's energy trading and bidding framework as it is aimed to be adaptable and flexible.

Although the IEC61850 standard is flexible and general but it is not BESS to aggregator specific and this research once to exploit that flexibility and develop a simple but effective protocol that fully exploits the IEC 61850 fundamentals. For example because MMS allows devices to reconfigure themeslves

This researcher haven't come across latency requirements or specific bandwidth requirements for this type of application in the literature it aims to find and document acceptable values.

2.10 Conclusion

A review of distributed renewable energy systems was undertaken. A discussion of its benefits in the smart grid was discussed as well how it is linked to a market based trading system. The importance of real-time communications in such a system was also discussed. To enable real-time communications, the IEC 61850 was reviewed as an open standard that is capable of enabling a real-time energy trading system was reviewed. This literature review provides a clear understanding of the fundamentals of data communications in the smart grid and this will form the basis of this research and system development. The review also provided some communications for distributed control of energy systems fundamentals and wireless communications as a possible network architecture for this thesis have been covered.

Chapter 3

Research Plan

3.1 Hypothesis

"A solar feed-in tariff is a rate paid for electricity fed back into the electricity grid from a designated renewable electricity generation source such as a rooftop solar panel system or wind turbine." Energy Matters [2017]. As an example, feed-in tarriffs for Queensland are shown in Table 3.1 Solar Market [2017]. Looking at Table 3.1 it can be seen that all the retail energy providers have feed-in tariff of about 6c/kWh. During peak periods *prosumers* help to increase the grid to cop with demand by injecting more energy into the grid yet they still only get kk 6 c/kWh.

I hypothesise that with the introduction of aggregators and competition among these aggregators the *prosumer* will be paid higher prices than those shown in Table 3.1. The role of aggregators was introduced in section 2.3. When aggregators bid for the energy in *prosumers'* BESSs the *prosumer* will get a better price as it is in the best interest of the aggregator to secure the energy instead of the competition. This is particularly true during periods of peak demand.

Based on the above statements, the hypothesis can be drawn as follows:

"*An energy bidding and trading between* ***two or more aggregators*** *and a BESS will result in higher prices paid to the prosumer*."

Dependent variable: sell price (*the final price per kWh the prosumer gets after a successful bid and trade*)

Independent variables:-

Table 3.1: Feed-in Tariffs for Queensland (as on 20 January 2017).

Retail Energy Provider	Current Rate (per kWh)
AGL	6c
Origin	6c
Energy Australia	6c
Click Energy	6c, 10c, 11c
Ergon	6.348c

- *Number of aggregators:* Its hypothesised that the greater the number of aggregators in a trading group the greater the competition amongst themselves for the available energy in BESSs resulting in higher offers.
- *Total number of BESSs:* The assumption is that the number of BESS are in an energy multicast trading group affects the price the aggregators will offer.
- Reserve price (set to the benchmark price)
- Time of day
- Percentage energy available for sale

3.2 The Proposed Approach

From the established hypothesis in section 3.1, final energy prices offered to *prosumers* will need to be recorded and compared to a benchmark price, prices in Table 3.1 for example. A protocol suite will be designed and implemented in C/C++. Energy bidding and trading algorithms together with accompanying applications will be developed. Finally experiments will be run in Network Simulator 3 (NS-3) and data will be collected from NS-3 trace files. The data to be collected include the number of aggregators that participated in a bid, time of day, offer prices, bids and final sell prices. This is a **quantitative** research approach.

From the collected data, statistical analysis like getting mean prices and standard deviation will be performed. The data can also be used as input to machine learning algorithms. For example, using machine learning a *prosumer* might be able to predict the best time to sell energy or the best offer to accept at a particular time.

3.3 Research Significance

Electricity generation is the greatest source of greenhouse gas emissions, about 67% of electricity in the USA come from burning fossil fuels US EPA [2017]. In Australia about 86% of electricity comes from burning fossil fuels Origin Energy [2015] with renewable energy sources only making up 14%.

The research significance is substantial original contribution towards further reduction in greenhouse emissions by having more renewable energy source participants in electricity generation. This will be achieved by the research, development and demonstration of a framework and associated artefacts for real-time energy trading between distributed battery energy storage systems (DESSs) and electricity aggregators. When the feed-in tariffs are greatly improved more *prosumers* will join the smart grid as there will be a better financial incentive to do so. In summary the following are the benefits derived from this research:-

- A framework for real-time energy bidding and trading between battery energy storage systems (BESSs) and aggregators
- A protocol suite and associated messaging scheme to support real-time energy bidding and trading between BESSs and aggregators
- Energy bidding and trading algorithms, messages and applications
- An appropriate network architecture to support real-time energy bidding and trading
- Other studies can be based on this research like energy bidding and trading between EVs (Electric Vehicles) and aggregators. BESS to BESS (peer to peer) is another area that can benefit from this research. The protocol suite and algorithms could be easily adapted to satisfy this scenario.

3.4 Research Method

Since this research seeks to solve a practical problem by developing a framework for real-time energy bidding and trading, design and development of associated protocols and applications, it is a good candidate for **design science research methodology (DSRM)**. "Design science is the scientific study and creation of artefacts as they are developed and used by people with the goal of solving practical problems of general interest." Johannesson and Perjons [2014]. DSRM focuses on creation and on how things have to be done in order to attain goals Geerts [2011]. This results in the creation of artefacts. In DSRM artefacts are man made creations for practical purposes. "Such artefacts may include constructs, models, methods, and instantiation" Peffers et al. [2007]. In this thesis the man made creations (protocol suite, algorithms, applications, messaging structure) are for solving a practical problem, how to facilitate real-time energy bidding and trading. DSRM aims to come up with practical solutions to practical problems.

3.5 Research Framework

The conceptual framework for this research is in line with Design Science Research as shown in Figure 3.1. The framework is aligned with the following six activities of the DSRM proccess model Peffers et al. [2007]:

1. ***Problem identification and motivation:*** The problems and motivation of this research have already been discussed in Chapter 1, "Statement of Research Problem".

2. ***Definition of the objectives for a solution (Requirements):*** From the research aim and objectives as outlined in 1.4 and knowledge gathered in literature review (Chapter 2), the objectives for a solution are inferred.

3. ***Design and development (Artefact):*** This is where the artefacts like a suitable protocol, energy trading algorithms, messaging system and network services are designed and created. The network architecture, bandwidth and latency requirements analysis are done in this activity. The protocols, network services and applications will be developed in the C++ programming language in conjunction with Network Simulator 3 (NS-3).

4. ***Demonstration:*** NS-3 will be used to demonstrate the artefacts described above. It will be used to demonstrate the developed protocol suite, messaging systems, real-time energy trading and the proposed network architecture. Log file dumps and live animations will be used to illustrate the energy bidding and trading activity.

5. ***Evaluation:*** The first stage of the evaluation will be to look at the NS-3 trace files and see if they are in line with the research objectives and the hypothesis in 3.1. Statistical analysis will be used to evaluate the randomness of the results. Each simulation should

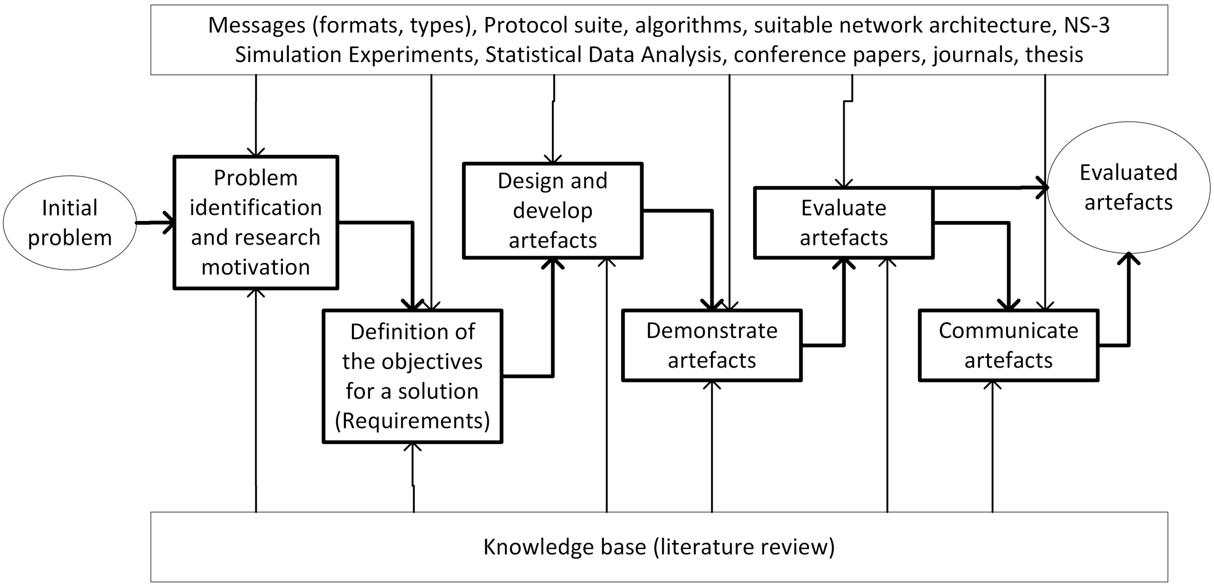

Figure 3.1: Conceptual Framework

result in statistically different energy offer prices, bid prices and sale prices. The second stage is running the experiments on a QUT live testbed and compare the results with the simulation results. To ensure replicability seed numbers will used in random number generators. Whireshark protocol analyser tool will be used to evaluate the developed protocol.

6. ***Communication:*** The research problem as described in Chapter 1 and the importance of the research as outlined in 3.3 will need to communicated to researchers and related audiences. The artefacts and the rigor of their design can the published in conference papers and journals.

Table 3.2 below shows how the research questions and objectives are aligned to the DSRM activities described above.

3.6 Resources and funding required

- Open-source software (Network Simulator 3 (NS-3), C++ compiler, Python, WireShark and Linux) will be used for the research.
- QUT Power Systems school will provide access to a test network.

Table 3.2: DSRM ctivities, research questions, objectives and data

Research Question	Research objective	DSRM Acitivity	Data collection method
What is the suitable network architecture?	Find a suitable architecture that satisfy latency and bandwidth requirements	1,2,4,5,6	NS-3 Trace files
What protocols should be developed at an ISO layer identified for this type of application?	Investigate, design and develop a suitable protocol	1,2,3,4,5,6	NS-3 Trace files
What application layer network services and messages should we have?	Investigate and develop application layer network services and messages	1,2,3,4,5,6	NS-3 Trace files

- QUT has provided a laptop computer.
- Access to QUT HPC (High Performance Computing) for running simulations at scale.
- Second Computer Monitor at my QUT Workstation so I can work from both home and QUT.

3.7 Individual Contribution to the Research Team

I will be the sole contributor of the research.

3.8 conclusion

A preliminary hypothesis has been formulated and the dependant variables to test the hypothesis have been identified. The research approach is quantitative and a design science research methodology will be followed. A conceptual framework in line with the six activities the design science research methodology has been illustrated. The main data source will be log files and NS-3 trace files. The research significance and the required resources have been pointed out.

Chapter 4

Progress to Date

4.1 Completed Coursework

Semester 1, 2016:

IFN001 AIRS - Advanced Information Retrieval Skills (completed)

Semester 2, 2016:

INN700 - Introduction to Research

INN701 - Advanced Research Topics (60% complete, the remaining 2 modules will be completed in Semester 2, 2017)

4.2 Requirements Analysis

To implement the proposed energy trading system real-time messages need to be exchanged. The aggregators need to know how much energy is available in a BESS and what percentage of the available energy energy can be traded. The registration and bidding processes all involve message passing. Proposed message types are shown in Table 4.1. Different messages have different delay characteristics and priorities as show in Table 4.2

Table 4.1: Message Descriptions

Message	Description
Register	A BESS or Aggregator sends a multicast message to join the energy trading group
Query	Aggregator sends a multicast message querying BESSs if they have spare energy for sale
Response	BESS responds to a query message by sending a unicast message to an aggregator indicating total available energy, what percentage is available for sale and the price per kWh
Bid	Aggregator sends a unicast message indicating total required energy and an offer or counter offer
Accept Bid	BESS sends a unicast message to aggregator accepting bid
Bid Confirmation	Aggregator sends BESS acknowledging bid and energy trading commences
Reject Bid	BESS sends a message to aggregator rejecting bid or offer
Terminate	Either BESS or aggregator can terminate trading for a variety of reasons including 1) transaction finished, 2) transmission and distribution errors
Device Failure	Critical message indicating a BESS failure.
BESS Status	Periodic keep-alive and status messages from BESS to aggregator. Payload include battery drainage, voltage, etc

Table 4.2: Delay and priority requirements

Message	Priority (0-high, 100-low)	Max delay (ms)	Source	Destination
Register	80 (low)	5000	BESS or Aggregator	Multicast group
Query	70 (low)	3000	Aggregator	BESS
Response	15 (high)	500	BESS	Aggregator
Bid	10 (high)	500	Aggregator	BESS
Accept Bid	5 (high)	500	BESS	Aggregator
Bid Confirmation	5 (high)	500	Aggregator	BESS
Reject Bid	50 (medium)	1000	BESS	Aggregator
Terminate	10 (high)	400	BESS or Aggregator	BESS or Aggregator
Device Failure	0 (very high)	200	BESS	Aggregator
BESS Status	60 (medium)	2000	BESS	Aggregator

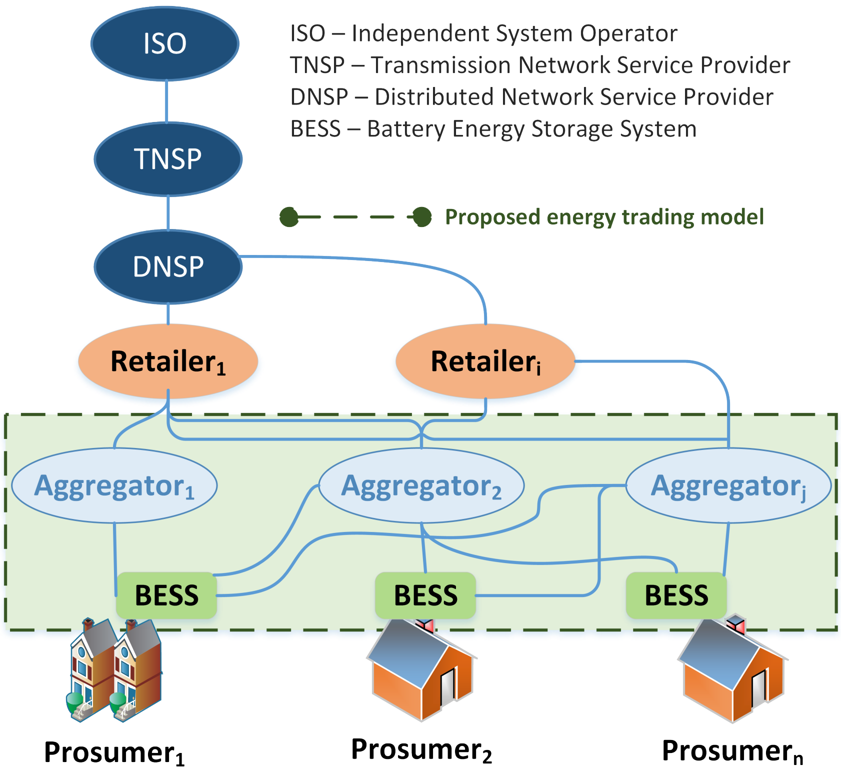

Figure 4.1: Current and proposed energy trading model

4.2.1 Model Development

The proposed model is shown in Figure 4.1.

4.2.2 Energy bidding and trading process and message passing

The proposed model is shown in Figure 4.2

4.3 Publications

A paper was submitted to an IEEE conference paper for Chicago meeting. Although it was rejected I got good comments and constructive criticism that allowed that has been incorporated into a revised paper that will be submitted for a conference in Beijing in November.

I am currently writing a journal paper that builds on the ideas presented in the conference paper.

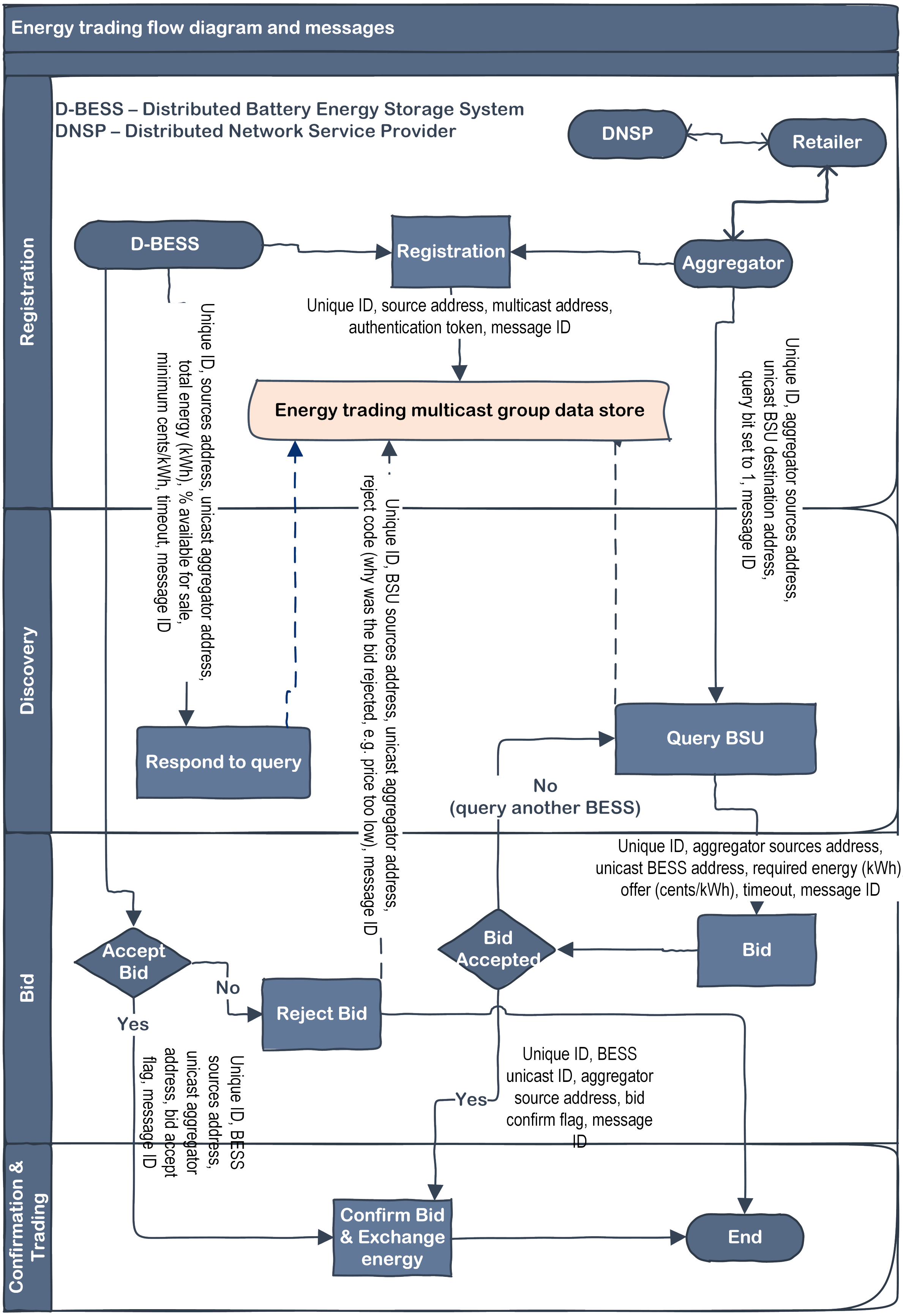

Figure 4.2: Energy bidding and trading flow diagram

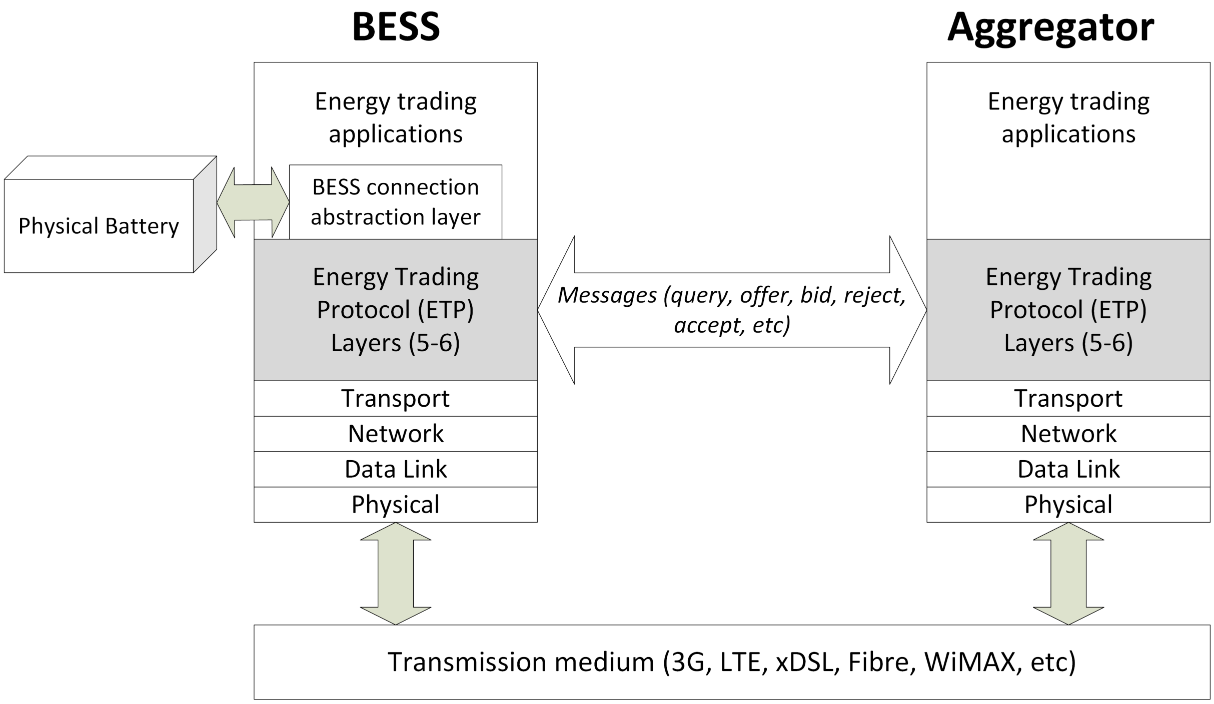

Figure 4.3: Energy trading protocol (ETP) in relation to the OSI model and a physical battery

4.4 Preliminary protocol design

The energy trading protocol will be implemented at layer 5 and 6 of the OSI model as shown in Figure 4.3 using integrated layer processing (ILP). The message header and payload is shown in Figure 4.4.

4.5 Research Tools

Mendeley reference manager will be used to manage literature obtained from such databases as IEEE Xplore, Science Direct and Scopus. Linux containers (LXD/LXC), WireShark, Gnuplot and Network Simulator 3 (NS-3) will be used for running and analysing the simulations.

MESSAGE TYPE	**MESSAGE ID**	**DEVICE ID**	**TTL**	**MESSAGE TYPE PAYLOAD**
0 – Register	(System timestamp)	(System timestamp)		0 – {}
2 – Response				2 – {Total Energy, percentage available for sale}
3 – Bid				3 – {offer price, cents/kWh}
4 – Accept Bid				4 – {total energy, percentage, sale price}
5 – Bid Confirmation				5 – {total energy, percentage, sale price}
6 – Reject Bid				6 –{0}
7- Terminate				7- {}
8 – Device Failure				8 – {}
9 – BESS Status				9 – {remaining energy, health status code, voltage, rate of discharge}

Figure 4.4: Energy trading protocol (ETP) message header and payload

Chapter 5

The Next Steps

5.1 Protocol implementation

The protocol as depicted in Figure 4.3 will be implemented in C++, tested and evaluated in NS-3.

5.2 Experiment design and NS-3 simulations

5.3 Test-bed Evaluation

5.4 Literature expansion

Work on Nash equilibrium and game theory need to be expanded further. The aggregators want the cheapest prices and the *prosumers* what the the best prices. In our model there is multi-way competition might the be mathematically an

5.5 Publications

It is expected that a conference paper and two journals will be written.

Chapter 6

Timeline for Completion

The research has a completion target of April 2019. Milestone details are shown on Figure 6.1 on the following page.

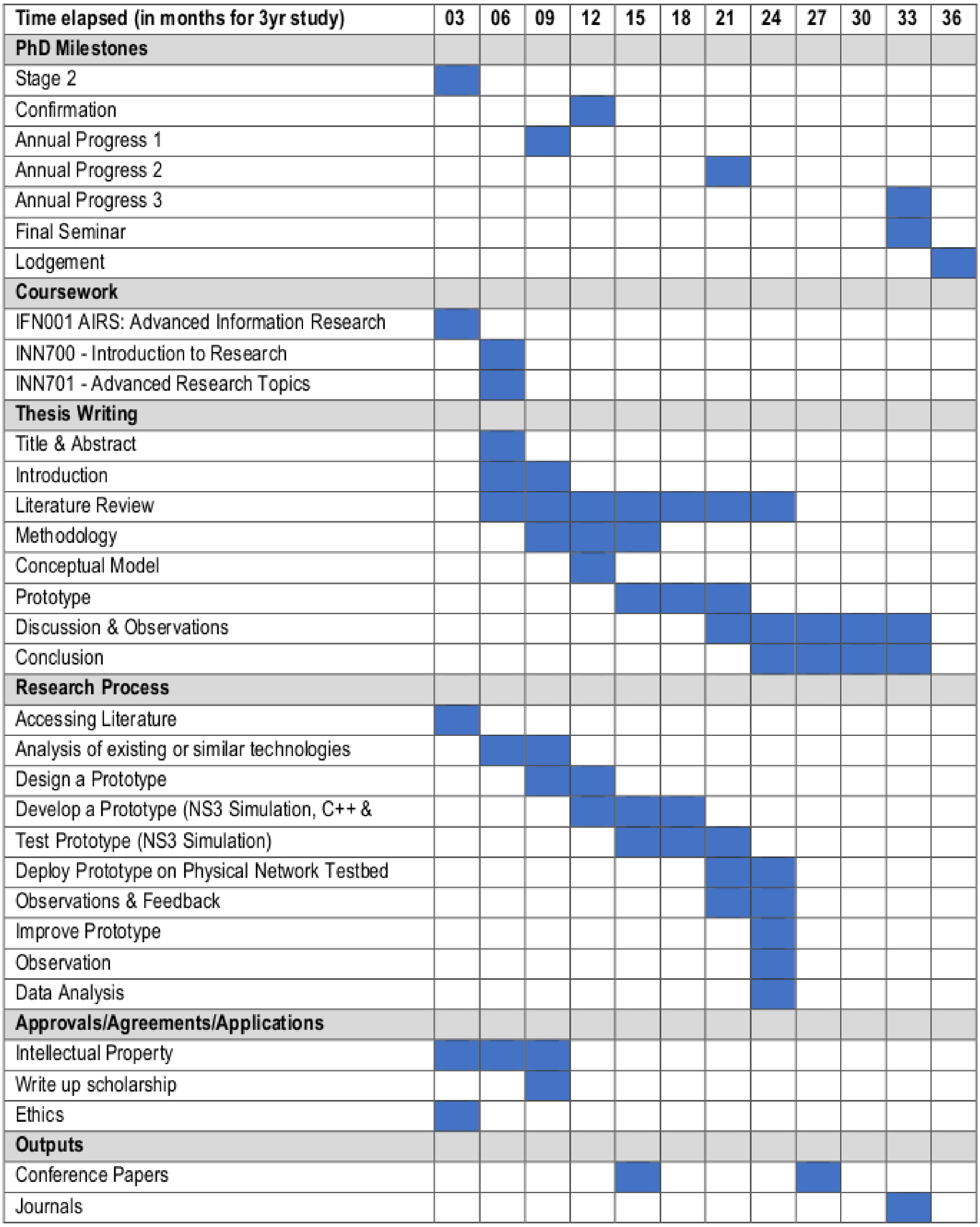

Figure 6.1: Timeline for Completion

Appendix A

A.1 Research Ethics Integrity and Safety (REIS)

The REIS certificates are shown in Figures A.1 and A.2 respectively

A.2 Intellectual Property

The intellectual property arising from this research is the property of the participant in its entirety. QUT will not own any intellectual property arising from this research.

A.3 Health and Safety Statement

This research does not involve any hazardous materials nor does it raise any health and safety issues.

A.4 Ethical issues

The research project does not involve human or animal tests. There are no ethical issues.

Figure A.1: Research Ethics Integrity and Safety (REIS) - Module 1

Figure A.2: Research Ethics Integrity and Safety (REIS) - Modules 2-5

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