Cellular Network System Design

Author: Craig Wang   Student ID: U4848572
Year: Semester 1, 2014   Lecturer: Chris Browne
ENGN2225 Systems Engineering Design – Design Portfolio
The Australian National University

Abstract

The current cellular network is under significant phase change due to the ever-increasing consumers' demand and the development of 4G/5G networks. In this portfolio, we are going to look at cellular networks from a systems engineering perspective and propose an improved design over the existing network. We start from the basics to look at design requirements and then apply various techniques including House of Quality and functional analysis. As the design grow more mature, we provide functional block diagrams and attribute cascade, which will aid the verification and the evaluation of the designs. The evaluation show that our design is superior in comparison of the existing networks over a range of aspects.

Keywords: System Engineering, Cellular Network, System Design Process.

Introduction

System is an interconnected set of elements that is coherently organized in a way that achieves something. (Meadows, 2009) In the modern world, more and more complex systems arise as a result of the rapid development of technology and evolvement of the society. In order to intuitively and efficiently reach a design, system design process should be used invariably.

In this portfolio, we are going to investigate into the design of cellular networks. In short, the cellular network is a wireless network distributed over sections of land area that called *cells*. Each cell consists of a cell site known as *base station* and numerous *mobile stations* which are devices with wireless communication capability. The base stations in the cells together form the backbone of a cellular network, which is our design focus in this portfolio. The core functionality of cellular networks is to provide cellular services including SMS messaging, phone calls and mobile internet. CSIRO recently find the growing pace of wireless communication demand in Australia could lead to a bandwidth spectrum crunch by 2020. (CSIRO, 2014) In addition, one of the three Chinese mobile operators China Mobile have already deployed more than 1 million base stations and consuming more than 13 billion kWh of electricity in 2011. Another 200,000 4G base stations are already in their deployment phase. (Chih-Lin, 2012) With these findings as our core motivation, we apply system engineering design approach to find a feasible solution that appropriately addresses customer and design requirements.

Outline of design portfolio

In this portfolio, we treat entities which operate such cellular networks as our customer. The topics and techniques that are applied in this portfolio is summarised in Table 1.

Table 1: A summary of the topics and techniques applied in this portfolio

Topic	Technique and Outcome
System Scoping	***System Boundary Chart:*** Gained clear understanding of which elements are considered in our design
Requirement Engineering	***Pairwise Analysis:*** Quantitatively ranked the importance of customer requirements
	House of Quality: Mapped design requirements to engineering characteristics and studied their relationships
System Function Definition	***Concept Generation:*** Generated design ideas and decided to focus on the meeting demands and energy aspects
	FFBD: Spotted redundant links during the transmission processes and obtained design insight on eliminating them
Subsystem Integration	***FBD:*** Studied system architecture and obtained further design insights at the subsystem level
System Attributes	***Attribute Cascade:*** Linked customer requirements with system attribute, found strongly linked subsystems
Verification & Evaluation	***Testing Procedures:*** Set out testing procedures of system attributes and helped evaluation.
	Evaluation Matrices: Quantitatively compared different designs and concluded the proposed design is the best
Design Communication	***Communication:*** Pitched proposed design to customer using schematics and life-cycle cost diagram.

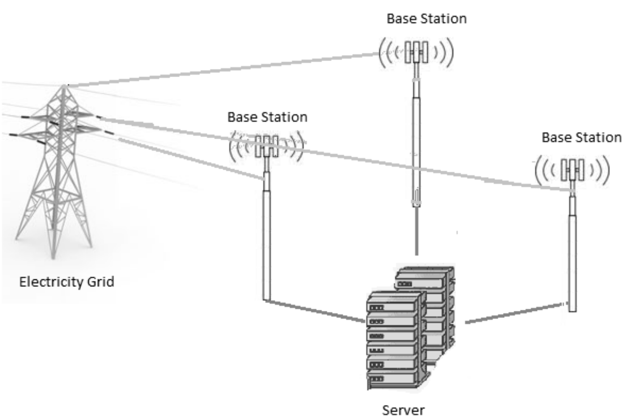


Fig. 1a. Existing Network Design

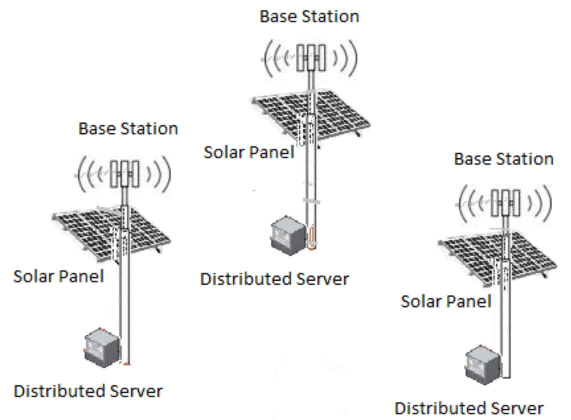


Fig. 1b. Proposed Network Design

An overview of the proposed design is shown above. Figure.1a shows the schematics of the existing network where each base station is connected to a central server for communication purposes and to the electricity grid for power supply. The proposed design shown in Figure.1b eliminates the unnecessary connections and each base station becomes highly modular with their own power supply through solar panels and their own distributed server. We discuss in detail the processes of systems engineering approach that we have used to reach the proposed design.

System Scoping

In this portfolio, we treat network operators as the customer hence the design focuses on the infrastructures of the cellular network and its characteristics. The system boundary chart in Table 2 is an important first step of the system design process, it summarize the scope of the system and limits the extent of the design.

Table 2 System Boundary Chart for Cellular Network System

Internal	External	Outside
Transmission Unit Processing Unit Power Unit	Server Signal Consumer Power Source	Model of Mobile Devices Natural Disasters Manufacture of Base Stations Relay Stations

The Internal list contains the elements which should be included in our design consideration, each of them has an impact on the overall performance of the network and can be tuned to satisfy customer and design requirements. The components in the Internal list constitute the hardware and software of the network infrastructure.

The External list consists of major input and output of the cellular system, which is mainly transmission signal that includes the request and responses of each transmission. However the transmission signal are commanded by the consumers who use mobile devices, they should also be included in the external list. Lastly, although power sources is not part of the infrastructure of cellular network, it is essential for the operation of the network. The Outside elements are not in the scope of our system however they can be considered in a more extensive project.

Requirements Engineering

Customer Requirements

One of the initial steps of systems engineering approach is translating the customer requirements into design requirements. Based on research and prior knowledge, we come up with the following customer requirements and their mapping to design requirements as shown in Table 3. However in reality, it is necessary to communicate effectively with customers before and during the project in order to fully understand their requirements.

Table 3 Mapping of Customer Requirements to Design Requirements

Customer Requirements	**Design Requirements**
Satisfy demand	Satisfy consumer demand
Secure	Protect against hacking
Efficient	Energy efficient
	Cost efficient
Legal	Meet international standards
	Minimise impact to city landscape (Small Size)

Pairwise Analysis

Design priorities have been generated based on Pairwise Analysis Chart in Table 4, we rank the importance of design requirements and therefore establish our design priorities. It is necessary to conduct this process since it is likely that not all of requirements can be fully satisfied when there is trade-off between them, such that sacrifices need to be made on those requirements of lower importance. In particular, security measures implies communication security which depend on how well the transmission signal is protected and how much privacy consumers can have small size means the hardware size of the base station, it can vary from the size of an antenna to the size of Telstra Tower in Canberra.

Table 4 Pairwise Analysis Chart for Cellular Network Design Requirements

Design Requirements	Protect against hacking	Energy Efficient	Meet International Standards	Satisfy Consumer Usage Demand	Small Size	Low Cost	Sum	Rank
D1: Protect against hacking		1	1	0	1	1	4	**2**
D2: Energy Efficient	0		0	0	1	1	2	**4**
D3: Meet International Standards	0	1		0	1	1	3	**3**
D4: Satisfy Consumer Usage Demand	1	1	1		1	1	5	**1**
D5: Small Size	0	0	0	0		0	0	**6**
D6: Low Cost	0	0	0	0	1		1	**5**

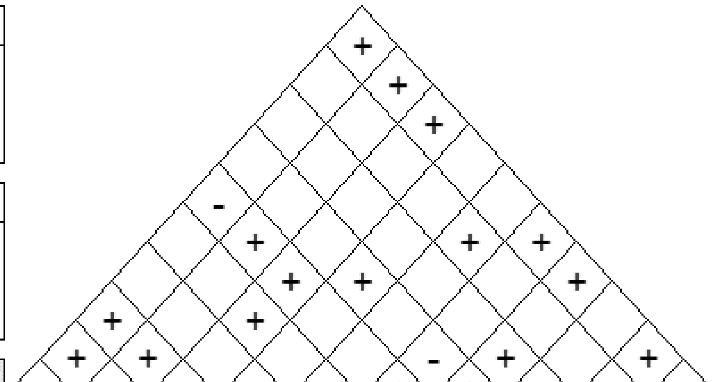
It can be seen that ‘Satisfying Consumer Demand’, ‘Security Measures’ are ranked as our two top design priorities. Although our direct customer is network operators, their source of revenue is the consumer. Therefore satisfying the consumer’s needs including coverage region, data throughput, quality of phone calls and data privacy falls into our top priority. The small size and low cost are ranked among the requirements of lowest priority, it is likely that there are trade-offs between D4 and D5, as well as between D1 and D6. When it comes to certain constraints, the requirements of small size and low cost could be sacrificed. Then we map the design requirements into engineering characteristics in the House of Quality (HoQ) analysis as shown in Figure 2.

House of Quality

Relationships	
Positive	+
No Relationship	empty
Negative	--

Relationships	
Strong	9
Moderate	3
Weak	1

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



ID Number	Relative Importance	Design Requirement \ Engineering Characteristics	encryption level of transmission	standby energy consumption	peak load energy consumption	type of standards	radiation level	throughput	user coverage region	size of structure	maintainance cost	operational cost
		Direction of Improvement	◇	▼	▼	◇	▼	▲	▲	▼	▼	▼
ID1	2	protect against hacking	9			3						
ID2	4	energy efficient		9	9	3						
ID3	3	meet international standards	3			9	9	3		3		
ID4	1	satisfy consumer demands	3			3		9	9			
ID5	6	minimum impact to city landscape		1	1		1			9		
ID6	5	cost effective		3	3						9	9
		Metric/TPM	Order	kW	kW	Name	Sv	Mbps	%	m	$	$

Figure 2: House of Quality for Cellular Network System (UNIVERSITY OF TEXAS-PAN AMERICAN, 2013)

The design requirements from Pairwise Analysis are mapped to engineering characteristics in HoQ for better design insights. Those characteristics are measurable and can be directly addressed using technical specifications. HoQ is systematic method of studying design requirements and engineering characteristics. It makes the relationships between them clear and aids the design by highlighting important aspects.

It can be seen in Figure 2 that every characteristics is related to at least one other characteristic, we are able to extract some useful design insights from this. By looking at our top design requirement ‘Satisfying User Demand’, it has strong relationships with several engineering characteristics including encryption level, type of standards, throughput and user coverage, those then maps to a second level of relationships with other characteristics especially with operation cost. If we solely focus on improving ‘Satisfying User Demand’ related characteristics according to their direction of improvement, the burden on the cost can be significant and leads to an invalid design if there is a cost constraint although the cost is the least important in our design requirements. Therefore we cannot make a design decision based on only one piece of information, but rather looking at a bigger picture. Further, there are many trade-offs exist in the system, they are easy to spot by looking at their direction of improvements and +/- relationships. For instance, standby energy consumption and throughput have a positive relationship yet they have opposite directions of improvements. Those findings provide useful information on our design process, especially we can easily know the side-effects when we are looking at possible changes. We are going to brainstorm about some design improvements and look at one particular function of the network for further investigation.

System Function Definition

Concept Generation

After a clear understanding of the customer requirements and design requirements, a concept generation process can be initiated to come up with ideas on the design. Without being too technical and over complicating the problem, we focus on two design requirements: namely ID5 satisfy consumer demands and ID2 energy efficient.

Table 5 Concept Generation

ID5 satisfy consumer demands	**High density deployment**
	5G networks
	Increasing frequency spectrum
	Increase transmit power
	On-site server to reduce delay
ID2 energy efficient	**Renewable energy source**
	On-site power supply
	Efficient hardware
	Power generation

The options such as 5G networks and increasing frequency spectrum are beyond the reach of network operators since they are both regulated by governments. In addition, network operators often do not directly participate in the hardware development and therefore cannot change the characteristics of the hardware. Hence the rest of the viable design options are highlighted in bold. After careful consideration, we take a look at a network design that has on-site power supply that is able to harvest renewable energy; and has on-site distributed server to reduce delay.

Functional Flow-Block Diagram

Functional Flow-Block Diagram (FFBD) is a useful technique in functional analysis, it provides a link between design requirements and the operational steps of the system. In the cellular network setting, the key functionality is providing cellular services to end consumers. Although the exact types of transmission varies from data, voice to video, they all essentially binary bits in origin. Therefore we study the process of how a transmission is initiated and ended in terms of its FFBD, as shown in Figure 3.

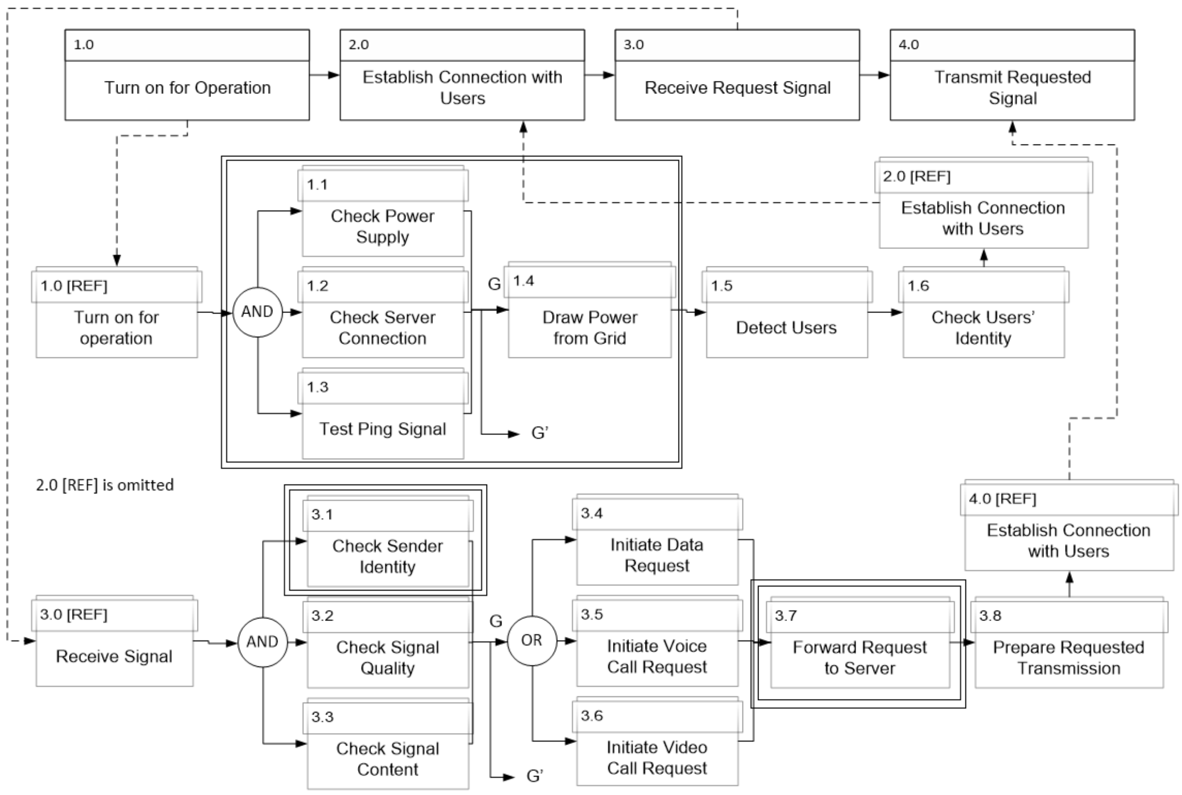


Figure 3: Functional Flow-Block Diagram (FFBD) for Existing Cellular Network System (Changes compare to Figure 4 proposed design are highlighted by double box)

In order to avoid technical aspects of the cellular network, we create a simplified FFBD and demonstrate our design process using two second level flows, namely from 1.0[REF] to 2.0[REF] and from 3.0[REF] to 4.0[REF]. Immediately after 1.0[REF], there are three blocks concern about the fundamental operation of the base station, namely check its power supply, server connection and transmission ability. Those three blocks 1.1-1.3 can be ran without any particular order as it is shown in an AND gate. If any of the tests fails, it results a NO GO path such that appropriate actions need to be taken. Ideally a full FFBD should also include the NO GO path. Immediately after 3.1 and 3.2, there are three paths the flow can take, namely initiate either data, voice or video request. Only one of 3.3, 3.4 and 3.5 is needed to ensure the flow of the process, hence joint by an OR gate.

In terms of design insights, it can be seen that there is some preparation steps between 1.0[REF] to 2.0[REF] before an actual transmission occurs, this cause potential delays at consumer end which is not desirable. In addition, a conversation between the base station and the server is occurring at 3.6. This can jam up the network during peak load and hence increasing probability of dropped calls due to server overload. The existing networks are built on top of the GSM network which the infrastructure was suitable at that time. However as the demand of wireless communication from consumers exponentially increased over the past decade, the existing network is no longer a satisfactory solution. In order to avoid these drawbacks, we test our propose network architecture to see if improvements have been made on some of the aspects.

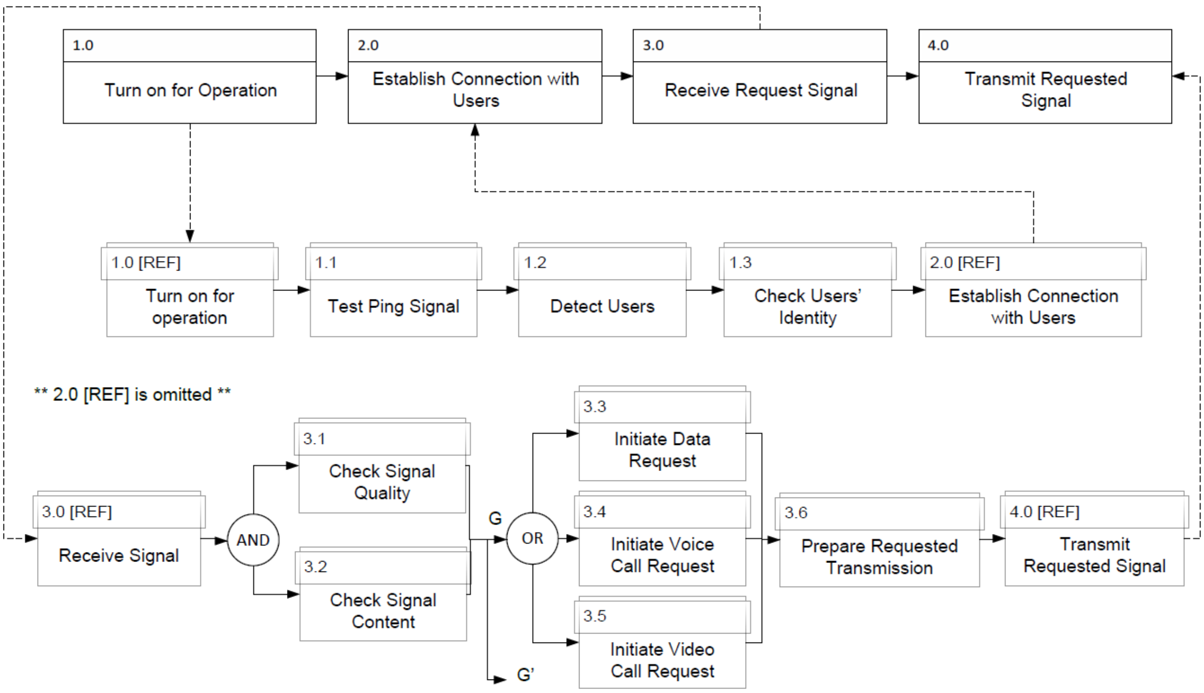


Figure 4: Functional Flow-Block Diagram for Proposed Cellular Network System

It can be seen in Figure 4, the FFBD for the refined network further simplifies on some of the processes. Notably between 1.0[REF] to 2.0[REF], by constructing an on-site power supply eliminate the necessity to check the power supply and draw power from the electricity grid.

In addition, an on-site server also helps reducing the delay time of a transmission request. By implementing on-site power supply and server, it creates a distributed cellular network where base stations can be plug-and-used. Such design improvements enhances the ability of the network to satisfy consumer demand while slightly increase the cost, as predicted by the HoQ analysis before. We look at how those design changes effects the subsystems of the network by drawing functional block diagrams.

Subsystem Integration

A Functional Block Diagram (FBD) not only communicates information regarding internal and external elements that was identified in System Boundary Chart, but also clearly reveals system architecture. It helps to recognize the modularity of the system and understand how the subsystems interface with each other hence simplifies the design process. The FBD of existing design is shown in Figure 5.

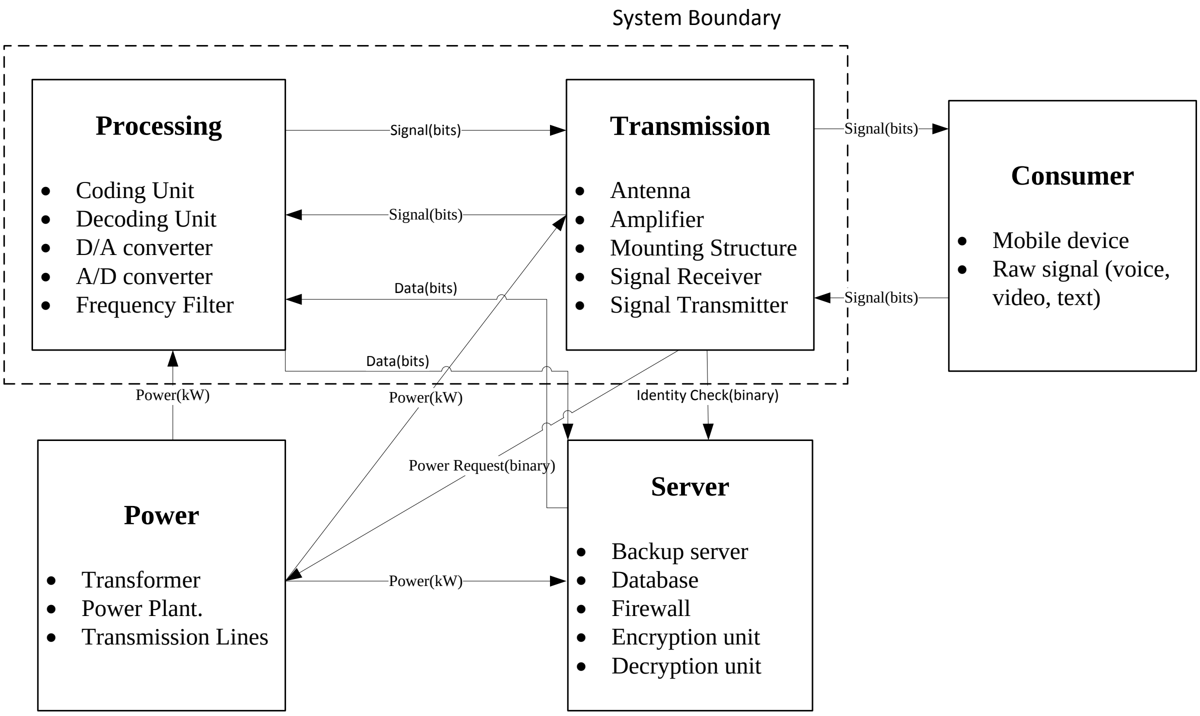


Figure 5: Functional Block Diagram for Existing Cellular Network System (BLANCHARD, 2011)

As it can be seen in Figure 5, the current base stations rely on external power and communicate with external server. This information aligns with the FFBD in Figure 3, and causes delay between transmissions during peak load and can potentially jam the traffic flow of the network. In addition, consumers only directly interact with transmission subsystem via transmitted signals. However there are many other interactions in and out the system, which can make the transmissions and the system vulnerable against security attacks. Using the design modification proposed before, that is implementing on-site power supply and server, can mitigate such problem effectively. The FBD of proposed design is shown in Figure 6.

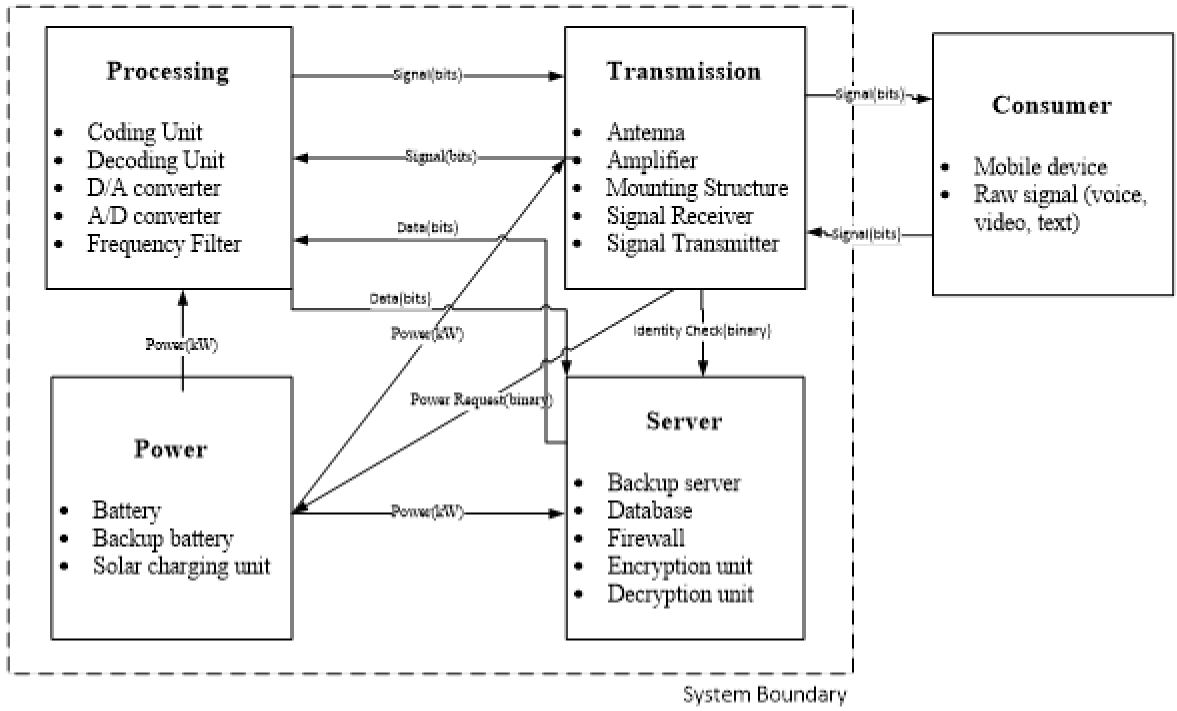


Figure 6: Functional Block Diagram for Proposed Cellular Network System

It can be seen that now the only subsystem that communication with external elements is the transmission subsystem, via its antenna and signal receiver/transmitter. Hence the design enhance security measures of the network by the eliminating its exposure to the outside world. In addition, interface within the system significantly reduce delay compare to interface with external elements. So far the design addresses the key problems we have discovered, we then look at specific attributes that the proposed network should have.

System Attributes

After preliminary system architecture is defined in the Functional Block Diagram, we move on to specify non-functional qualities that a good design should have. Attributes Cascade relate customer requirements to system qualities to ensure requirements are addressed in the final design. The primary attributes are the original design requirements, these are unpacked into secondary and tertiary attributes which are more specific features that address top-level attributes.

We break customer requirements that are at a higher level down into secondary and tertiary attributes. The tertiary attributes are ideal non-functional qualities of how our cellular network design should be. It can be seen that there are some paradoxical attributes such as 2.1.2 and 3.2.3, one says low transmitting power for energy efficiency while another says high transmitting power for high coverage to satisfy user need. In such situations, an optimal transmitting power should be determined in the background using appropriately designed algorithms.

Table 6 Attribute Cascade for Cellular Network System

Primary Attribute	Secondary Attribute	Tertiary Attribute	Related Subsystems
1.0 secure	1.1 transmission encryption	1.1.1 advanced coding algorithm	Processing
		1.1.2 multiple partial transmission	Transmission
	1.2 database encryption	1.2.1 self-checking ability for malware	Server
		1.2.2 coded database	Server
2.0 energy efficient	2.1 operational energy consumption	2.1.1 energy generation module	Power
		2.1.2 low transmit power	Transmission + Processing
		2.1.3 efficient coding	Processing
		2.1.4 meet international standards	Processing
	2.2 standby energy consumption	2.2.1 standby mode	Server
		2.2.2 efficient hardware design	Power
3.0 satisfy consumer demands	3.1 throughput	3.1.1 directional antenna	Transmission
		3.1.2 multiple antenna	Transmission
	3.2 coverage	3.2.1 dense deployment of base stations	Transmission
		3.2.2 cell size	Transmission
		3.2.3 high transmit power	Transmission

In addition, the Related Subsystems in Table 6 includes all of the subsystems which indicate none of the subsystem is redundant. The transmission subsystem appeared the most, it implies that it is related to lots of system attributes and hence when a change for the transmission subsystem is made. Power subsystem is relatively modular since it only appeared twice in the attribute cascade, this modularity allowed us to move the power subsystem from external to internal in the proposed design. The attribute cascade provides useful information for us to verify the design in the next step.

Verification and Evaluation

Design verification, evaluation and selection together are the final stages of a design process before communicating design with the world. It is the process of evaluating final designs against customer requirements with consideration of their relative importance. Before completing this process, several designs should already be in consideration. The most suitable design will be selected with strong quantitative and qualitative reasoning.

Verification

Design verification provide tools to demonstrate designs matches up against requirements, different testing methods can be applied to various system attributes. Procedures for two of the system attributes will be determined, namely A2.0 Energy Efficient and A3.0 Satisfy Consumer Demand.

A2.0 Energy Efficient (System Prototypes - Type II Testing): Energy efficiency mainly concerns about the energy consumption of the network, including operational consumption and standby consumption. As mentioned in *(Chih-Lin, 2012)*, the more than 13 billion kWh electricity used just by a single cellular operator in one year creates a significant amount of burden on the already stressed electricity grid. Hence this is an important system attribute to test. The energy consumption can be measured quantitatively by a certified electrician, an example of testing procedures can be set out as follows:

1. Set the base station hidden from the network
2. Turn base station ON
3. Measure the electricity consumption as the standby consumption
4. Reveal the base station to the network
5. Measure the electricity consumption throughout time
6. Measure the number of users and amount of data transmitted over the same time
7. Calculate electricity consumption per user and per unit data size

The test should be deemed fail either if standby consumption is over 30% of total energy consumption or if the power consumption per user exceeds some threshold, for example 20 Watts. Such testing should be carried out in a controlled environment for maximum repeatability for an actual base station, including controlled ambient noise signal, operating temperature and transmission standards.

A3.0 Satisfy Consumer Demand (Proof of Concept Testing): The highest customer requirements and the main purpose of cellular network is to provide communication services to consumers, hence it is necessary to make sure that the cellular network can satisfy the demands of consumers, this including providing a transmission speed and a high signal quality. Since it would be costly to prototype the entire network to test if demands are satisfied, the desired testing method is to use analytical models such as (Harpreet S. Dhillon, 2013). The test can be conducted as follows:

1. Implement the analytical model from (Harpreet S. Dhillon, 2013) in Matlab
2. Input network operators' design parameters including budget and location constraints
3. Input network infrastructure design including base stations' density, transmit power and types of power supply.
4. Run Matlab simulation to obtain performance metrics of the design such as the transmission speed trends and average signal quality

The test should be deemed fail either any of the consumer demands are not met by the design. This test can provide useful information on improving the design parameters, since it is easy to be conducted and the results are accurate representation of real performance. It should be repeatedly conducted for every design change.

Evaluation and Selection

Evaluation matrix is a quantitative method of comparing different designs against customer requirements and it leads to a decision process of coming up with the best design overall. The criterions are inherited from HoQ analysis and their importance is adopted from the result of Pairwise Analysis. These criterions are essential requirements for the design of the cellular network, and are ranked of highest importance in the analysis before. The previous generation GSM network (Rahnema, 1992), the existing 3G/4G network (Rao, et al., 2000) along with our proposed design are considered against each of the mandatory criteria. Since they are mandatory, a single 'Fail' will result exclusion of the design from further consideration.

Table 7 First Level Evaluation of Cellular System Designs

Mandatory Criterion	Design 1: 2G GSM Network	Design 2: Existing Cellular Network	Design 3: Our Design for Future Network
High Throughput	Fail	Pass	Pass
High Coverage	Pass	Pass	Pass
Meet International Standards	Pass	Pass	Pass
Prevent against Hacking	Pass	Pass	Pass

Since the 2G network was designed to support cellular services that only requires small amount of data such as phone calls and messaging, it is not suitable for the current high throughput demand of the modern consumer. This is also numerous source suggest that 2G network will be phased out around 2016. (GRYTA, 2012) Therefore it is dropped from our further consideration as a potential solution.

Table 8 Second Level Evaluation of Cellular System Designs

Criterion			**Design 2: Existing Cellular Network**		**Design 3: Our Design for Future Network**	
	Rank	Weighting	Assigned	Weighted	Assigned	Weighted
Satisfy Consumer Usage Demand	1	6	3	18	5	30
Security Measures	2	5	5	25	5	25
Meet International Standards	3	4	5	20	3	12
Energy Efficient	4	3	1	3	5	15
Low Cost	5	2	3	6	3	6
Small Size	6	1	3	3	5	5
		Total		75		93

The weighting of desired criteria in Table 8 is determined based on pairwise analysis. Each design is score against the criterion, with values 1, 3 and 5 indicating non-compliance, partial compliance and full compliance respectively. Ideally the scores should be based on the verification results, in this case we assign the score based on our knowledge and new articles referenced in this portfolio. (Chih-Lin, 2012) (CSIRO, 2014) (GRYTA, 2012) (Harpreet S. Dhillon, 2013) The total score is then calculated, Design 3 for future network received 93 points which surpass Design 2 by 24%. The higher score indicates that the proposed design better satisfies the criterions that have been determined to be of more importance. Therefore from the quantitative result of evaluation matrix, the proposed design is the best of all three. In addition, the matrix shows strength and weaknesses of each design which allows us to make further improvements on the design in the future iterations.

Design Communication

Looking at the network as a system, we have use several techniques to investigate into existing design and proposed a design to address key customer requirements and improve over the existing design. The proposed design will not only benefit network operators in terms of business profit, but also enhance the publicity by building a greener and more environmentally friendly network. Although some capital investment is expected, the long term saving can be substantial especially given the current demand of cellular services from consumer and the rapid growth of the network.

“Australian businesses have experienced an almost 80 per cent increase in electricity prices since 2009 and there are more rises on the way” (PEARSON, 2014) A major expenditure of the cellular network operators come from the energy bills, a large amount of power is required for the operation of base stations, the central server and various other supporting electronics components. Therefore a key to increase the long term profit of network operators is to reduce the energy bills. This can be accomplished by increasing the capital investment of constructing base stations with on-site power supply and distributed server.

For example, one of Australia’s largest network operator Optus currently owns more than 5,600 3G base stations, (Optus, 2014) they alone consume approximately 150 million kW of electricity annually, which is equivalent to more than 50 million AUD per year (Department of Finance, Government of Western Australia, 2014). With on-site power supply installed, each base station will rely solely on renewable energy sources, which brings $50 million savings just on the electricity bill of 3G base stations. We provide an approximate life-cycle cost plot is attached in the Appendix A to further illustrate the financial savings.

A summary of the key strengths and weaknesses of the existing design and the proposed design are shown in Table 9 and Fig 7.

Table 9 Summary of Design Comparison

	Figure 1a: Existing Network	**Figure 1b: Proposed Design**
Strength	Centralised security	High energy efficiency Short delay and faster traffic
Weakness	Low energy efficiency Communication delay	High capital expense High maintenance cost
Approximated Life-Cycle (10 years) Cost	$594 Million	$310 Million

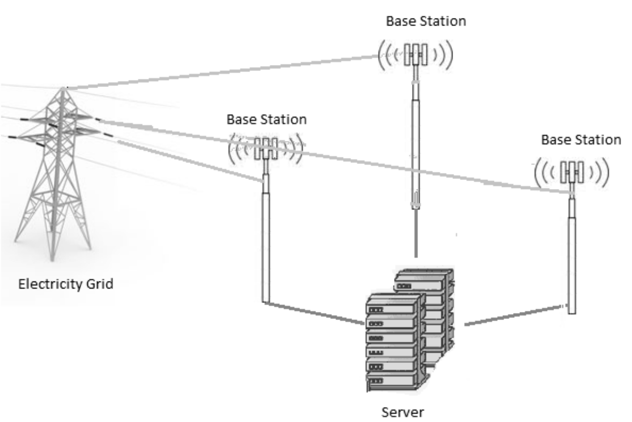


Fig. 7a. Existing Network Design

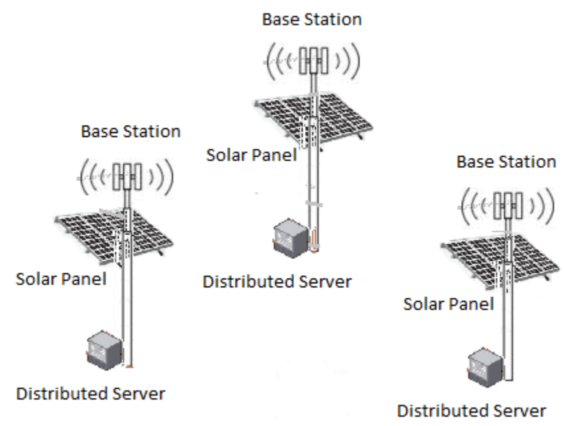


Fig. 7b. Proposed Network Design

Conclusion

In this portfolio, we used systems engineering approach to design an improved cellular network based on existing designs. An efficient and logical design process is followed to reach the proposed design. We started from the fundamentals to look at customer requirements and then applied various techniques to learn about key design insights. As we have more information, an improved design is proposed and explained in terms of FFBD and FBD. Afterwards, we set out testing methods to verify the design and using existing evidence to evaluate the design in comparison with others, which concluded that the proposed design is overall the best. Finally we communicate our approach and present the proposed design, constructing on-site server and power supply, to the cellular network operators.

Acknowledgement

Thanks Chris Browne (Browne, 2014), Yimeng Jiang and group members of Engineering A Better Plan for fruitful discussion and valuable feedbacks throughout this systems engineering design course.

Last Update: 10/05/2014 Place: Canberra, Australia

Contact: u4848572@anu.edu.au

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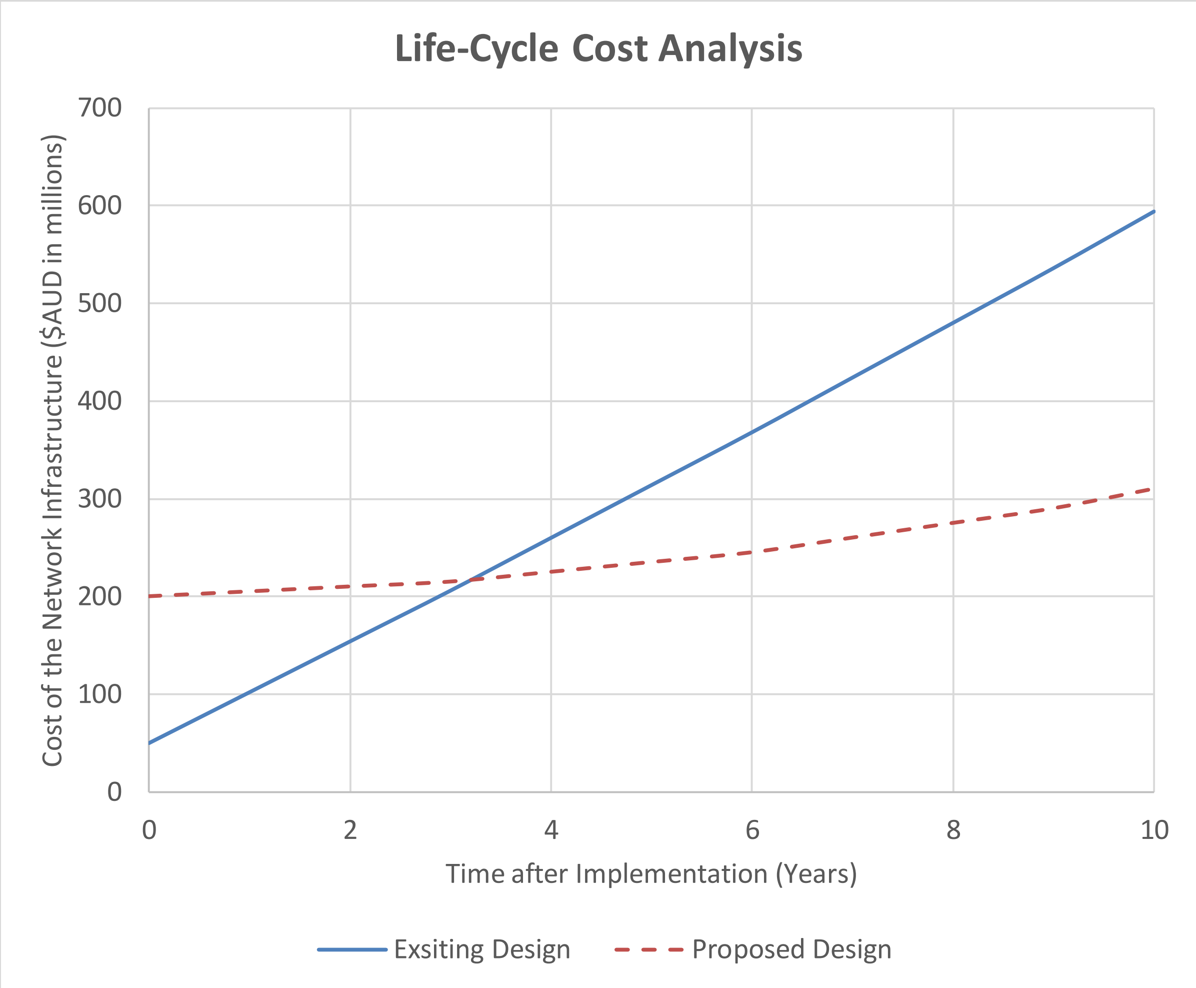
Appendix A:


Life-Cycle Cost Analysis
700
600
500
400
300
200
100
0
Cost of the Network Infrastructure ($AUD in millions)
0
2
4
6
8
10
Time after Implementation (Years)
Exsiting Design
Proposed Design