A Cost-effective Microcontroller-based Iridium Satellite Communication Architecture for a Remote Renewable Energy Source

by

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DEDICATION

This thesis is dedicated to my parents.

ABSTRACT

The Iridium Satellite System (ISS) is able to provide global communication. Distributed Generation (DG) dispatchibility requires collection and transfer of data from the field as well as monitoring and potentially remote control of the generators. Hence, this research develops a low-cost architecture and studies the feasibility of utilizing the ISS, which has Low Earth Orbit (LEO) satellites, with a 9601 Short Burst Data (SBD) transceiver for data communications.

A cost-effective microcontroller-based Iridium SBD satellite communication architecture is developed. Optimization of the telemetry data per SBD session is done to make the system more cost effective. The system is tested and the end-to-end time delay aspect of the data transmission is studied and recommendations drawn on the usability of the developed communication system for Supervisory Control and Data Acquisition (SCADA) for a Remote Renewable Energy Source (RRES) for its monitoring, maintenance and dispatchability.

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Abbreviations

AM	Amplitude Modulation
ATC	AT Commands
AR	Amateur Radio
CCS	Custom Computer Services
CEP	Circular Error Probable
DC	Direct Current
DCE	Data Communication Equipment
DG	Distributed Generation
DGCS	Distributed Generation Communication System
DISA	Defense Information Systems Agency
DoD	Department of Defense
DTE	Data Terminal Equipment
ECC	Energy Control Center
ECS	ETC Communication Subsystem
EEPROM	Electrically Erasable Programmable Read-Only Memory
ED	Environmental Data
ESS	Earth Terminal Controller SBD Subsystem
ETC	Earth Terminal Controller
FA	Field Application
FDMA	Frequency Division Multiple Access
GSM	Global System for Mobile communications
ICD	In-Circuit-Debugger
IMEI	International Mobile Equipment Identity
ISM	Industrial, Scientific and Medical
ISS	Iridium Satellite System
ISU	Iridium Subscriber Unit
ITU	International Telecommunication Union
LED	Light Emitting Diode
LEO	Low Earth Orbit
LOS	Line-of-Sight

MCU	Microcontroller Unit
MD	Maintenance Data
MOMSN	MO Message Sequence Number
MO	Mobile Originated
MT	Mobile Terminated
MTMSN	MT Message Sequence Number
NLP	Non-Linear Programming
OPGW	Optical Fiber Ground Wire
PC	Personal Computer
PD	Power Generation Data
PIC	Programmable Interface Controller
PME	Power Maintenance and Environmental
QPSK	Quadrature Phase-Shift Keying
RI	Ring Indicator
RM	Radio Modem
RRES	Remote Renewable Energy Source
SBD	Short Burst Data
SEP	SBD ETC Processor
SMPS	Switch Mode Power Supply
SMS	Short Messaging Service
SPI	Serial Peripheral Interface
SPP	SBD Post Processor
SCADA	Supervisory Control and Data Acquisition
TDMA	Time Division Multiple Access
UART	Universal Asynchronous Receive Transmit
UTC	Coordinated Universal Time
VA	Vendor Application

List of Symbols

N_{pg}	Number of Power Data (PD) sub-frames
N_{mi}	Number of Maintenance Data (MD) sub-frames
N_{ei}	Number of Environmental Data (ED) sub-frames
a	Parabolic constant
x	Abscissa values
y	Ordinates
h	One of the coordinates of the vertex of a parabola
K	One of the coordinates of the vertex of a parabola
K_1	Quadratic constant in Inequality (3.4)
K_2	Scaled offset in Inequality (3.4)
K_3	Offset in Inequality (3.4)
K_4	Offset scalar in Inequality (3.4)
A	Objective function coefficient of N_{pg}
B	Objective function coefficient of N_{mi}
C	Objective function coefficient of N_{ei}
R	Objective function
S	Number of combination of the choices of N_{pg}, N_{mi} and N_{ei}
i	Maximum value of sub-frames

Chapter 1

1. Introduction

To form a viable alternative to central generation of electricity, it is important that the DG sources are integrated and dispatchable requiring DG sources to be monitored and controlled using a communications infrastructure that is both cost-effective and reliable [1]. The specifications of a DG Communication System (DGCS) often depend on factors such as cost, telemetry requirements, control functions and feasibility of various communication technologies.

The remoteness of some DG sites makes it impractical for common communication technologies based on broadband copper and wireless to satisfy the DGCS requirements in a cost-effective manner. More specifically, the availability of high-speed networking depends on the installation of infrastructure when the DG generators are installed. When not available, alternative communication strategies such as point-to-point wireless Radio Modems (RMs) [1], cellular modems, or satellite modems (or combination thereof) should be considered; for low data volumes, the Iridium-based systems may be less expensive than the alternatives.

In extremely remote situations, or when a redundant system is required, a satellite modem with low hardware cost and global coverage complements the requirement of remote access to DG sites. Hence, the Iridium communication system with global access from pole to pole competes well for the low-cost redundant system for data telemetry for low data volumes. Since comparatively expensive in terms of data transmission, the thesis first focuses to develop a cost-effective architecture and tests the capability of the Iridium satellite modem. It then develops a smart software application with an optimization algorithm for the data bytes and limits the data transmission to a “need to know” basis at the Energy Control Center (ECC). To manage the smart application requirements, a Programmable Interface Controller (PIC) microcontroller will be used to control the satellite modem.

Some parameters to be monitored at the ECC from the DG sites include: voltage, current, real and reactive power, power quality, harmonics, transients, flicker and connection/fault status [2] as well as the Maintenance Data (MD) related to the field equipment and the Environmental Data (ED). Hence, to meet the telemetry and control functions for the DG sites, a data acquisition system at the DG site with an ISS would provide sufficient link contingencies at times of a failure or when it is the only viable communication link. For redundancy, the envisaged communication system link for the DG site to the ECC is in Figure 1.1.

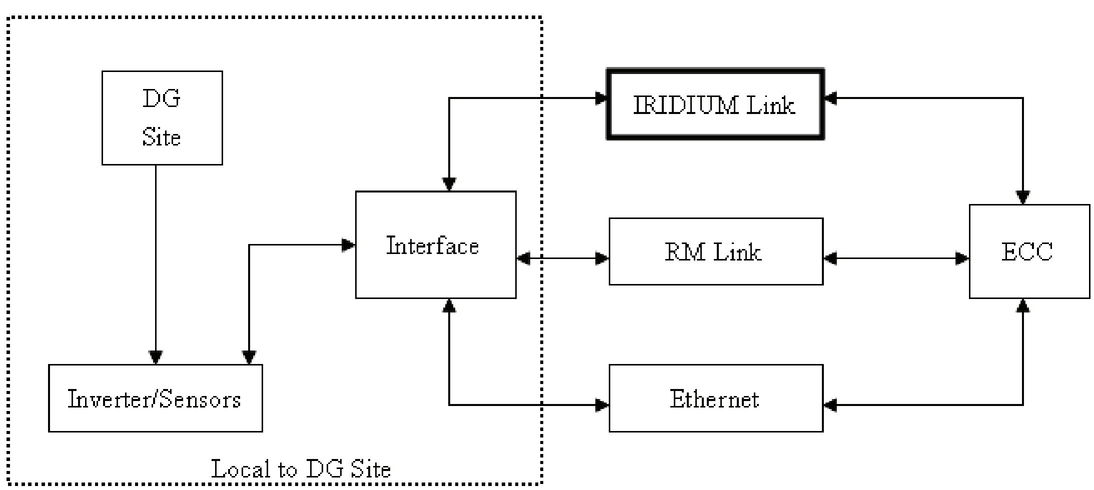


Figure 1.1: Overall system communication link

1.1 Literature Review

In 1987 Motorola engineers proposed the ISS concept; a constellation of simply constructed LEO satellites that could be built, launched and replaced economically. In the year 1998, Iridium LLC completed the constellation of 66 satellites with 100% launch success [4]. In December 2000, a group of private investors led by Dan Colussy organized and named the company Iridium after acquiring the operating assets of the bankrupt Iridium LLC. Based in Bethesda, Maryland, U.S.A., Iridium LLC, a privately held company provides global satellite voice and data communications solutions with coverage of oceans, airways and even polar regions [5]. Globalstar is another LEO satellite system which claims to cover all the land mass of the Earth with 44 active satellites, though the services are not available at the poles as its orbit is inclined at 52 degrees.

With the deregulation of electricity markets, policies are available to facilitate interconnection of electric grids and small DG systems. However, dispatchability and reliability still present technical barriers for small DGs to play a significant role in the open market [3]. The Iridium SBD transceivers were made available, targeting mainly application development in the areas of field force automation and remote asset tracking [4]. Hence, a suitable application specific communication system design for monitoring of the DGs at the ECC with Iridium SBD transceivers could improve and alleviate the problems of reliability of DG. Also, the system could be extended to make the DGs dispatchable, depending on the cost benefit of dispatchability vis-à-vis the investment and the running cost of the system. The solar-powered ocean observatory using acoustics and 9522 Iridium transceivers has successfully transmitted more than 150 MB of data since its deployment in May 2004 [6]; it gives more assurance that the conceived system would work making DG more reliable and dispatchable.

The general trend of electrical utilities around the world now has been towards replacement of the ground wires on the high voltage lines with Optical Fiber Ground Wire (OPGW) for communication and SCADA functions [31]. OPGW serving the function of the ground wires for lightning protection on high voltage lines and at the same time having multiple optical fibers for communication makes it an attractive business opportunity as well as a reliable source of communication for SCADA functions for the electrical utilities. A disadvantage of OPGW is that the information typically propagates only at two thirds of the speed of light in optical fibers. Also, Marihart indicates the communication by OPGW as one of the appropriate technologies for SCADA functions for many electrical utilities [7]. However, in cases of DG formulated with RRESs, the proposed low-cost ISS for data acquisition and communication for monitoring and possible control under certain circumstances is felt to be a more suitable and viable option. Also, this system could be used as a contingency communication system in case of failure of the primary communication system, as the billing is per the volume of data transferred.

1.2 Background

This section provides in brief, the background information and concepts related to this thesis. First the concept of DG is introduced followed by the ISS. The basic architecture of Iridium is introduced and specifically the SBD architecture is discussed in some detail. Also, a brief introduction is given about the tools used for the architecture development namely the PIC microcontroller, the Custom Computer Services (CCS) C compiler, and the Non-Linear Programming (NLP) to solve the non-linear optimization problem.

1.2.1 Distributed Generation

DG is generally formulated using small modular electricity generators at sites close to the customer load. Often based on renewable technologies (wind, solar, tides and fuel cells), it has it own economic, social and environmental benefits as compared to central generation. DG of power is becoming more common, mainly as a result of increased demand of electricity as well as the requirement to reduce the impact in the environment from traditional sources of power generation with fossil fuels and nuclear fuels [9]. With the growth of DG sites, feeding the loads locally or it being interconnected with the electric grids, a cost-effective monitoring and control system needs to be developed for it to be reliable and also for receiving the maximum benefit from the value added services given by the DG. Also, with increased DG trends, DG needs to be made dispatchable where dispatchability means that the sources of electricity can be dispatched/provided at the request of power grid operators, i.e. turned on or off on demand.

1.2.2 Iridium Satellite System

Iridium is a LEO satellite system at about 780 km from the Earth surface in 6 polar orbits [29] [30]. It provides mobile satellite services for voice and data for hand-held personal telephones and transceivers. Point-to-point communication at any location on the Earth surface is made possible with the portable phones/modems connecting to the satellites with inter-orbit and intra-orbit handoffs which in turn communicate to the Earth station for routing to the destination [10].

SBD is one of the data services provided by Iridium, where an application can send and receive SBD messages ranging from 1 to 1960 bytes (maximum) using small transceivers. The 9601 SBD transceiver is one which is designed to support the SBD service of Iridium. Frequency Division Multiple Access (FDMA) / Time division Multiple Access (TDMA) is used as the channel access scheme and the system uses a 50 kbps data rate and Quadrature Phase-Shift Keying (QPSK) modulation format on an 8.28 ms time slot and 41.67 kHz-wide channels [11]. The L-band frequency range of 1616 to 1626.5 MHz (10.5 MHz of bandwidth) is used for up-link and down-link with satellites and the Ka/K-band frequencies for inter-satellite communication. It has 240 channels of 41.67 kHz and approximately 2 kHz guard bands between channels. The Iridium network has 80 simultaneous users per cell, in 2150 active cells for a total network capacity of 172,000 simultaneous users [12].

Figure 2.1 shows the SBD system architecture and SBD call routing, where ETC means the Earth Terminal Controller, ECS means ETC Communication Subsystem, SEP means SBD ETC Preprocessor and SPP means SBD Post Processor. The various elements of the SBD architecture consists of the remote Field Application (FA) which here is the Iridium Subscriber Unit (ISU), the Iridium Satellite Constellation, the Earth Terminal

Controller SBD Subsystem (ESS) located at the Iridium gateway, the internet and the Vendor Application (VA).

In setting up an SBD communication system, it is only possible to configure one type of delivery method i.e. either ISU-ISU or ISU-e-mail [13], which is represented in Figure 1.3 with light and bold connecting lines, respectively. The communication system developed in this thesis is the latter delivery type.

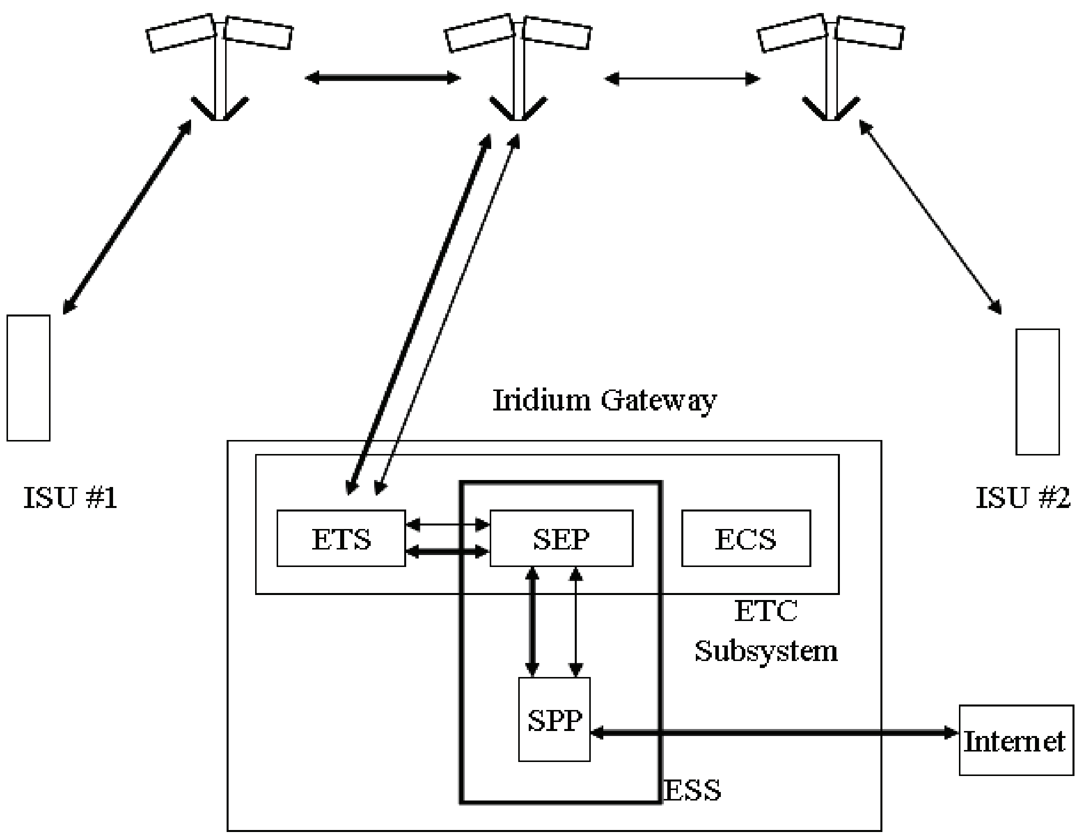


Figure 1.2: SBD call routing [13]

The ESS is responsible for storing and forwarding messages from the ISU to the VA and storing messages from the VA to forward to the ISU. The ISU communicates with the ESS via the Iridium satellite constellation. The interface between the VA and the ESS uses standard internet mail protocols to send and receive messages. Mobile Terminated (MT) messages are sent to the ESS using a common e-mail address, identifying the specific ISU by encoding the unique ISU International Mobile Equipment Identity (IMEI) in the subject line of the e-mail. The data message is transmitted as a binary attachment with the e-mail. The Mobile Originated (MO) messages are delivered to a specific e-mail address that is configured when the IMEI is provisioned.

1.2.3 PIC and CCS C

The PIC18F8722 Development Kit from CCS, Inc. is used for the microcontroller-based architecture of the 9601 SBD transceiver. The development kit has a prototyping board which has a PIC18F8722 connected to a potentiometer, a pushbutton, three Light Emitting Diodes (LEDs), an RS-232 level converter connected to the C6/C7 Universal Asynchronous Receive Transmit (UART) and the G1/G2 UART, and an In-Circuit-Debugger (ICD) connector as shown in Figure 1.3. The CCS C Compiler is developed by CCS, Inc. exclusively for the PIC® MCU (microcontroller unit). Hence, it is a good optimized compiler for Microchip parts. The 16-bit compiler used for programming the PIC8722 is named PCH.

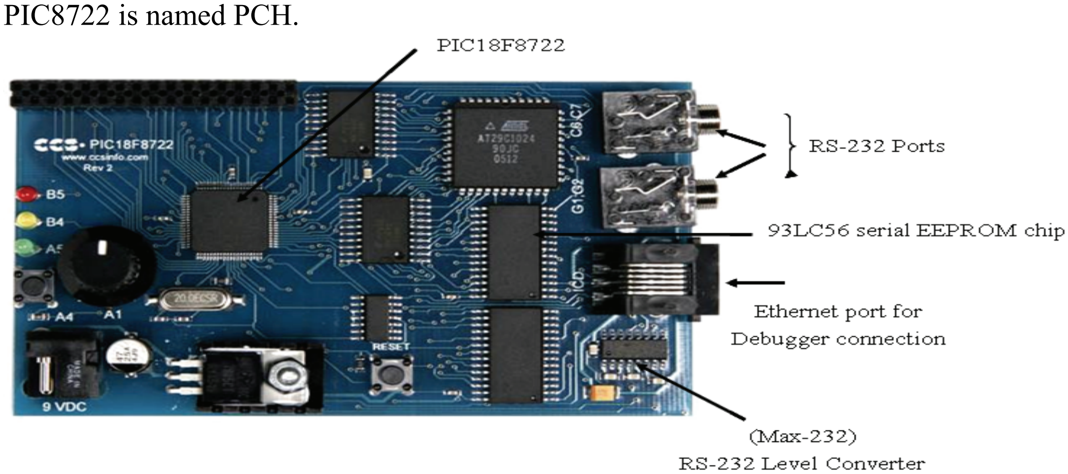


Figure 1.3: PIC18F8722 prototype board layout

1.2.4 Non-Linear Programming

NLP is the process of solving a system of equalities and inequalities, collectively termed constraints, over a set of unknown real variables, along with an objective function to be maximized or minimized, where some of the constraints or the objective functions are non-linear. In this thesis, the NLP problem is developed through the constraints and the objective function. The constraints are then solved for the variables using NLP. An exhaustive search algorithm and the built-in MATLAB® toolbox functions are used to solve the NLP and the results are compared. The variables are then fed to the objective function and the one which gives the maximum is taken as the optimized solution.

1.3 Thesis Contribution

The major contributions of this thesis are listed below:

- this thesis presents a cost-effective microcontroller-based Iridium satellite communication architecture for RRES (DG),
- a standalone microcontroller-based communication system with the 9601 SBD Iridium transceiver is developed and tested for MO and MT messages and the timing and delay analysis of the Iridium SBD service is documented,
- the SBD data packet is optimized with NLP for cost effectiveness, limiting the data to a “need to know” basis at the ECC and also for making the communication system intelligent; and
- finally, this thesis recommends the effectiveness of the Iridium SBD communication link for the monitoring and control of an RRES.

1.4 Thesis Organization

The chapters in this thesis are organized as follows.

- Chapter 1 provides the introduction to the problem, the solution methods, the basic background of the system and the tools.
- Chapter 2 gives the architecture of the microcontroller-based Iridium communication system with the 9601 SBD transceiver. It categorizes the data to be acquired at the RRES field and designs this application's specific data packets and its frequencies of collection depending on the limitations of the PIC18F8722 microcontroller. It draws the overall state diagram for the architecture of the data acquisition system as well as the communication system. Finally, the microcontroller-driven 9601 SBD Iridium transceiver is tested for the MO and MT messages and corresponding results are presented. Delay analysis on the MO and MT messages are done and recommendations given for SCADA functions of the RRES.
- Chapter 3 presents the need for optimization of the SBD data packets to make the Iridium SBD system cost-effective and intelligent for RRES monitoring. It then develops an NLP problem with constraints and an objective function for wind turbine monitoring, depending on physical conditions in the field and the wind turbine mechanics. The NLP is solved with MATLAB® which gives the sub-frame sizes, giving the maximum profit/benefit of communicating specific data to ECC.

- Chapter 4 presents a fixed- and variable-cost comparison amongst the SBD service of Iridium, Amateur Radio (AR), and point-to-point radio for various data volumes in perspective of an RRES monitoring system.
- Chapter 5 summarizes the work completed and recommends possible future research.

Chapter 2

2. Low-Cost and Controlled SBD Communication System Architecture for Remote Renewable Energy Source

2.1 Requirement of a Low-Cost Communication System

Integrating DG sources to electrical grids is important for making them dispatchable. This necessities DG sources to be monitored and controlled using a communications infrastructure that is both cost-effective and reliable [1]. Also, remote monitoring and control of the DG benefits the utilities regarding future planning, expansion and preventative maintenance of the installed systems. Data transfer, monitoring and control of DG can be achieved with various communication systems. Factors such as feasibility, availability of technology, the cost benefit of automatic monitoring and control, and most importantly, the budget determine the decision of opting for a particular communication system. Generally, in DG, high-speed communication facilities may not be available, due to the remoteness of its location, communications with point-to-point wireless RMs [1], cellular modems, and satellite systems are the general options. Hence, satellite systems with low hardware cost and global coverage complement the communication system for remote access of DG sites and the competitiveness of the Iridium system comes in places where there is no availability of any other forms of communications. Also, for low data volumes the Iridium system may be less expensive than the alternatives.

2.2 Communication Architecture for Remote Renewable Energy Source SCADA Functions

The low-cost architecture is developed with the 9601 SBD transceiver of the ISS. A microcontroller is used for controlling the volume of data transfer on a "need to know" basis at the ECC. Hence, to manage the smart application requirements, a PIC microcontroller is used to control the 9601 satellite modem. The overall architecture block diagram of the data acquisition and communication system which runs unattended for monitoring the RRES is shown in Figure 2.1, where SPI means Serial Peripheral Interface.

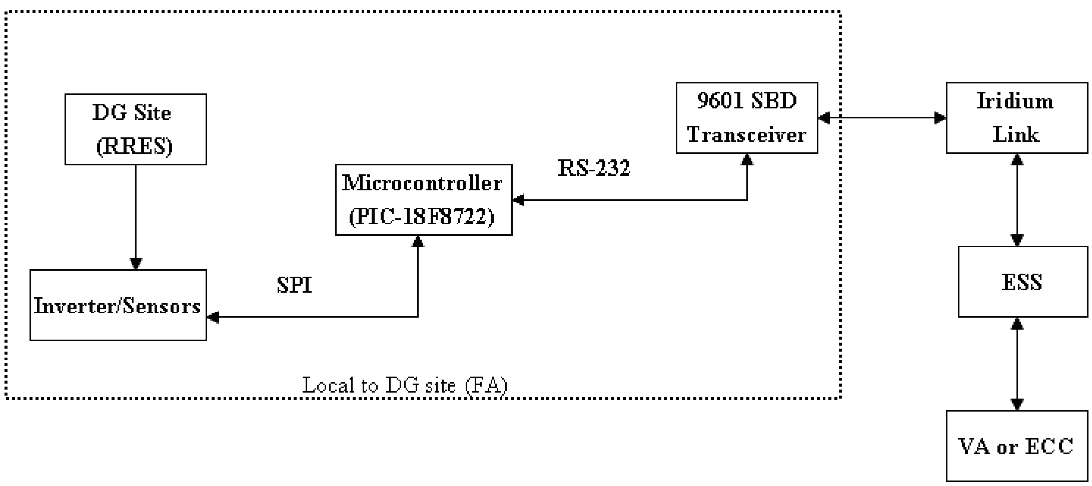


Figure 2.1: Architecture block diagram

The data required in the ECC from the RRES site is categorized as:

i. Power generation Data (PD),

ii. Maintenance Data (MD), and

iii. Environmental Data (ED).

The inverter contains the PD to be transmitted to the ECC and DG sensors are considered in place for the MD and ED collection. The FA reads the data from the inverter and the sensors, and subsequently logs the data in the Electrically Erasable Programmable Read-Only Memory (EEPROM) of the microcontroller. The details of the data structure for the various data types, the memory allocation in the EEPROM, the frequency of data logs and transfer to ECC are described in the FA design section.

The inverter has an SPI for communication to the FA. The PD, MD and ED are clocked from the inverter/sensors to the PIC through the SPI connection at specified times and at specified locations in the EEPROM. The PIC communicates to the 9601 SBD transceiver via an RS-232 communication link. The collected data at the end of 24 hours and after optimization for one SBD data frame of 205 bytes (as will be detailed in subsequent sections and Chapter 3), will be communicated to the ECC with the Iridium 9601 SBD transceiver automatically.

Once the MO SBD frame is optimized and written to the 9601 transceiver from the PIC, the satellite session is initiated which transfers the message to the ESS via the Iridium satellite constellation. At the ESS, the SBD message is converted into an e-mail message with an attachment and sent to the addresses configured for that particular IMEI SBD transceiver. The IMEI of the transceiver used here is 300 034 012 008 300 and the addresses configured for message delivery are q1a3t@unb.ca, b.petersen@ieee.org and jmeng@unb.ca. These three e-mail addresses basically constitute the VA.

For sending the MT message to the FA, an e-mail needs to be composed from one of the three e-mail addresses with a maximum message length of 135 bytes, with an attachment having a *.sbd extension and sent to the address sbd@iridium.com with the intended transceivers IMEI number in the subject line of the e-mail. Once queued in the ESS, a confirmation e-mail is sent to the VA and then the FA can at any point in time acquire the message with appropriate operations [14].

2.3 Field Application Design

The remoteness of the DG sites necessitates the use of systems which are automatic and self operational. Hence, a microcontroller architecture is designed to achieve this capability as well as this being a practical design, for the DG, which are generally in remote locations. The contention of the Iridium SBD 9601 transceiver as a communication system for the data telemetry from RRESs depends on how cost effective is the design of the architecture, how the data bytes for the SBD session are optimized, so that the ECC receives what is required at the lowest cost. This can be achieved by an intelligent FA design. Also, depending on the intelligence of the FA, apart from the data itself, the pattern and contents of the data sent can assist the ECC in making certain decisions, such as preventive maintenance and unscheduled maintenance, which may be of immense long-term value for an organization.

2.3.1 Hardware Design of Field Application

The main component of the FA hardware design is the PIC18F8722 on a prototyping board driven by a 20 MHz oscillator which is connected to the 9601 SBD transceiver. The PIC18F8722 prototyping board is as shown in Figure 1.3 in Chapter 1. The 9601 transceiver was connected via a DB9 RS-232 serial cable to the PIC for data transfer and to command the transceiver for satellite initiation. The SPI communication port is conceived to be used for data logging to the PIC's EEPROM from the inverter/sensors.

The hardware components for the 9601 SBD transceiver connection to the PIC and antenna are detailed in Figure 2.2. The transceiver was powered up with a regulated 6 Volt DC power supply from the power tray. The power tray used can regulate a 6 Volt supply output when given an input between 6 Volts to 30 Volts DC. The power tray also has an RS-232 serial interface, enable/disable switch and status LED. The PIC8722 was powered up with a 5 V DC adapter. The SBD transceiver was connected to a fixed-mast helical antenna with an 8 meter main cable, flexible jumper cables, connectors and lightning/surge suppressor for protection. The loss in the cables, connectors and lightning arrestor was checked so that it does not exceed 3 dB, which is as per the specifications.

The 9601 SBD transceiver pin configuration, the RS-232 connection details between the transceiver and PIC, the power tray features and specifications are given in Appendix A. For testing the communication link, the data from the inverter/sensors was assumed to have been received and stored in the EEPROM in specific address locations. This was done as the SPI connection could not be tested practically.

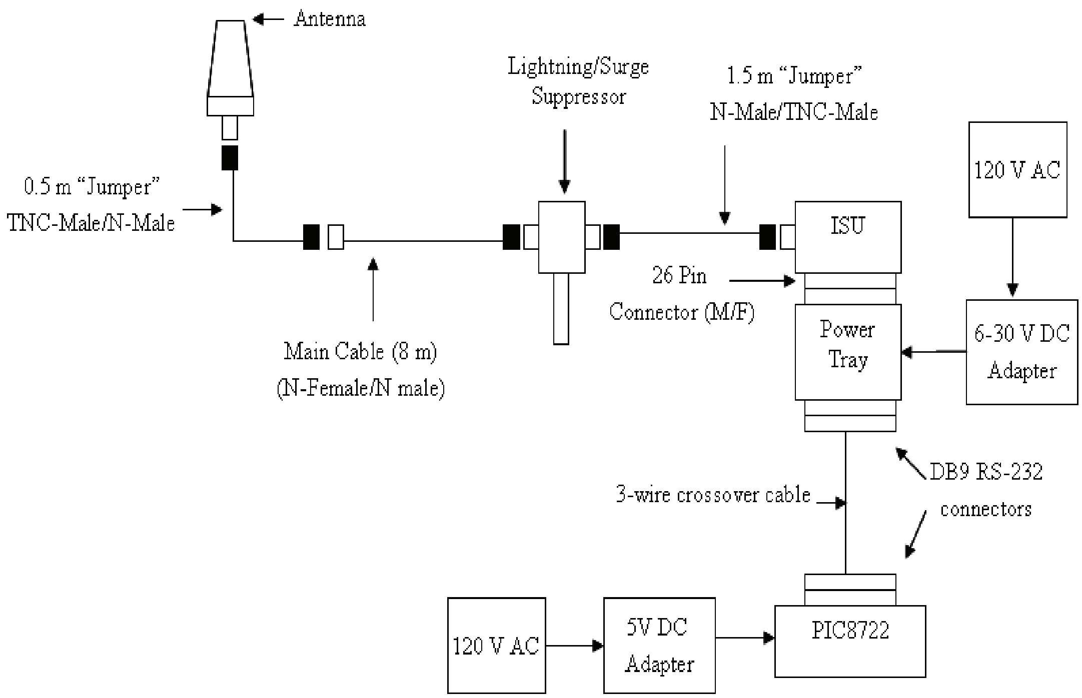


Figure 2.2: Hardware assembling block diagram

2.3.2 Software Design for Field Application

The hardware for the FA was designed targeting the overall minimum-cost design criteria for the system as well as meeting the overall functionality required by the system. The software part of the FA is designed so that there is control of the data that is acquired from the inverter/sensors and more importantly, the volume of data transfer, by controlling the 9601 SBD transceiver. Hence, the main function of the FA is to optimize the telemetry data as per the SBD frame size and requirements at the ECC and limit the data transfer, such that the telemetry function of the DG is met with the least cost.

The various components of the FA can be broadly classified into five modules;

i. acquire data and memory write,
ii. optimize the SBD frame (MO message) using NLP,
iii. limit, control and communicate the MO messages to VA,
iv. obtain the MT message at FA, and
v. check status of the inverter.

2.3.2.1 Interrupt Driven Architecture of FA

The code for the FA is written using the CCS C compiler and is responsible for the automatic initiation of the satellite session every 24 hours, after optimizing the SBD frame. The state diagram for the software architecture of the FA is given in Figure 2.3, where RI means Ring Indicator. It uses four of the timer interrupts and one pin interrupt available in the PIC8722 to perform the specific tasks at specified times. Hence, the program is implemented such that the various modules are executed when the interrupts for that particular module occur.

The 9601 SBD transceiver can be controlled with ATC (AT Commands). Hence, appropriate commands are written to the transceiver via the RS-232 connection and upon checking the responses from the transceiver for the particular command, the program flow is passed to the next part of the logic implementation, for obtaining the overall objective of the application.

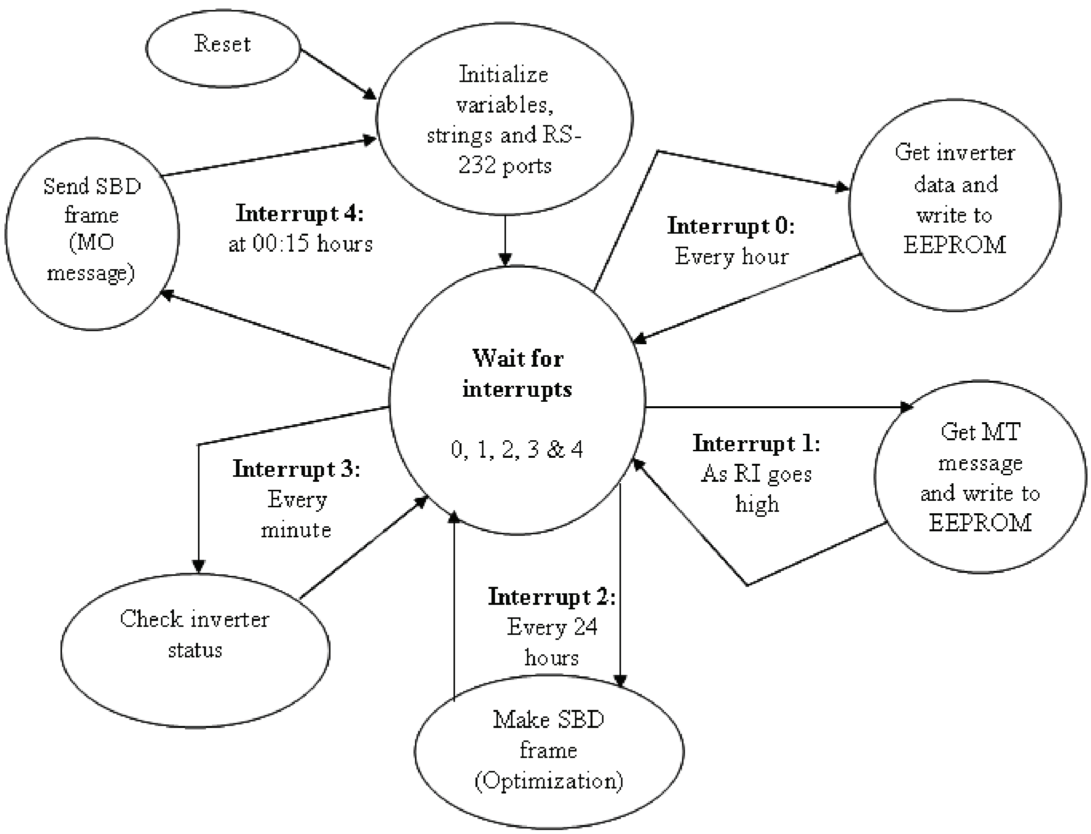


Figure 2.3: Field Application state diagram

The PD and ED are to be written every hour from the inverter/sensors to the EEPROM and the MD is to be written once every 6 hours. Hence, interrupt 0 is invoked every hour and on the 6^{th}, 12^{th}, 18^{th} and 24^{th} hours, the MD is written along with the PD and ED. The specific location in the EEPROM and the data size and format is discussed in the following sections.

The pin interrupt occurs when the RI pin goes high indicating that there is an MT message waiting at the ESS. Hence, the code to retrieve the messages is invoked when RI goes high and the received MT message is written to the specific location in the EEPROM for future retrieval.

Interrupt 3 is invoked every minute to check the status of the inverter. This interrupt is implemented so that if there is any emergency condition in the inverter then that status could be reported to the ECC. Hence, upon receiving the emergency-condition status of the inverter as "true", the control in FA is passed to send an SBD message to the ECC, with a notification of the inverter status.

Interrupt 2 is invoked at the end of 24 hours when the data is collected and written to the EEPROM. It then optimizes the SBD data frame by calculating the number of PD, MD and ED sub-frames competing to fill the SBD frame for transfer to the ECC. The maximum size of the SBD frame is 205 bytes. Each sub-frame is designed to be 5 bytes long. Hence, there are 41 bytes to be filled for an SBD session at the end of 24 hours. The details of the sub-frame size and format are described in later sections.

Interrupt 4 is invoked once per day, at 00:15 hours, for the initiation of the satellite session after writing the optimized SBD frame to the 9601 transceiver. The program then returns to acquiring the data for the next day overwriting the EEPROM addresses locations for the next 24 hours.

2.3.2.2 Data Frame Size and EEPROM Design

The three basic types of data collected are the PD, MD and ED. The size, format, frequency of collection and its location in the EEPROM is described in Table 2.1. Also described in Table 2.1 are the software modules, such as module 3 SBD optimization. It also gives the overview of all the processes that run to obtain the overall objective of sending an optimized SBD frame containing telemetry data of the DG at the end of a 24 hour period.

Table 2.1: Field Application design summary

Data Field/Process	Data collection/Process frequency	Data Format	EEPROM location	Interrupt	Remarks
PD	Every hour	Figure 2.4	0-359	Timer Interrupt 0	Module 1
MD	Every 6 hours	Figure 2.4	360-399		
ED	Every hour	Figure 2.4	400-639		
MT message receive	As RI goes high	-	845-979	Pin interrupt	Module 2
SBD frame optimization	Every 24 hours	-	-	Timer Interrupt 2	Module 3
Inverter status interrupt	Every 1 minute	-	980-1023	Timer Interrupt 1	Module 4
MO message send	At 00:15 hours	-	640-844	Timer Interrupt 3	Module 5

The inverter/sensors connected to the PIC via an SPI logs the data (PD, MD and ED) into the EEPROM when module 1 is called after every hour. The format of PD, MD and ED, which has sub-frames of PD, MD and ED data given by N_{pg}, N_{mi} and N_{ei}, respectively, to be collected from the field, is shown in Figure 2.4.

PD (15 Bytes)					
Start Byte	**Voltage (V)**	**Current (A)**	**Power (kW)**	**Checksum (Bytes)**	**Stop Byte**
1 Byte	4 Bytes	4 Bytes	4 Bytes	1 Byte	1 Byte

MD (10 Bytes)			
Start Byte	**Bearing Wear**	**Oil Condition**	**Stop Byte**
1 Byte	4 Bytes	4 Bytes	1 Byte

ED (15 Bytes)					
Start Byte	**Wind Speed (m/s)**	**Temperature (Deg)**	**Maximum Gust (m/s)**	**Wind Direction**	**Stop Byte**
1 Byte	2 Bytes	2 Bytes	2 Bytes	2 Bytes	1 Byte

Figure 2.4: Power Data, Maintenance Data and Environmental Data frame

Figure 2.5 shows the memory map in the EEPROM where the respective data in the format and size, in Figure 2.4, would be written so that it can be picked up by module 3, SBD frame optimization, which would be then picked by module 5 for MO message transmission.

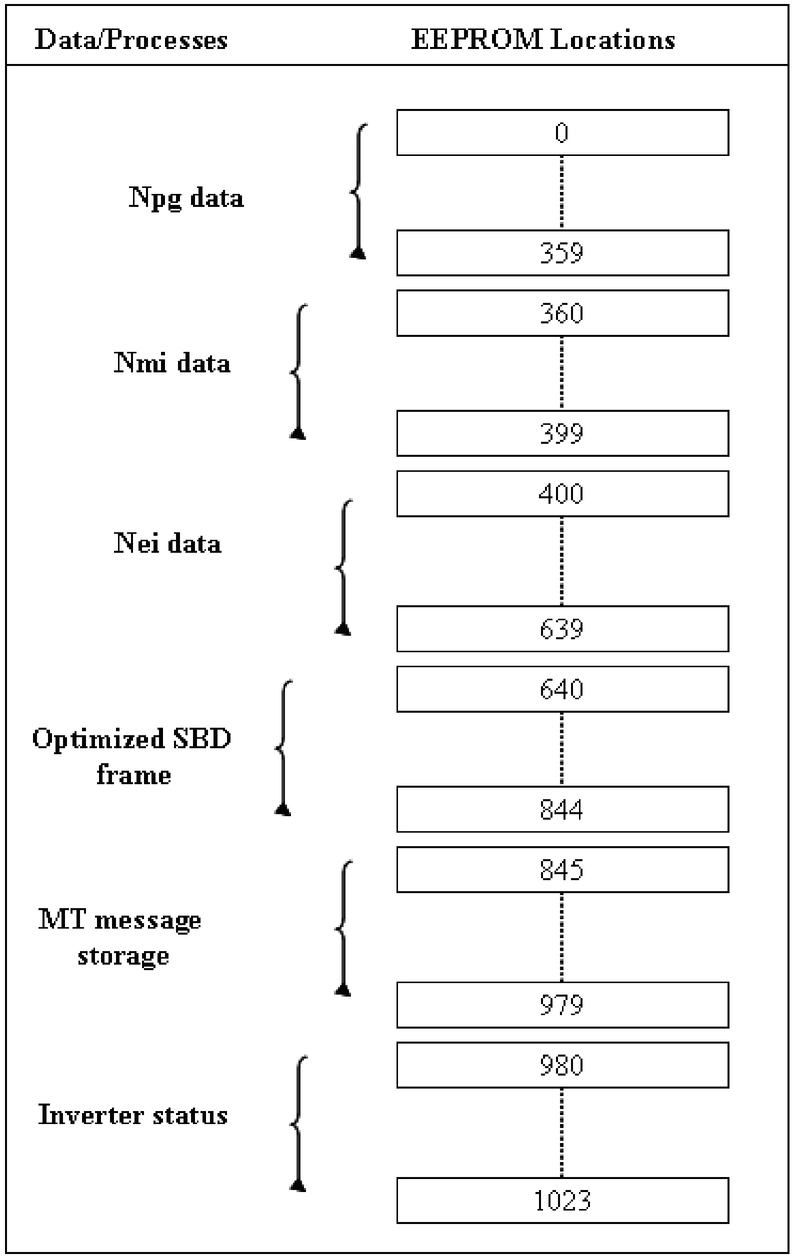


Figure 2.5: EEPROM addresses for data and processes of Field Application

The PD frame is 15 bytes long and is written to the EEPROM every hour. Hence, 360 bytes in 24 hours are written to the EEPROM as shown in Figure 2.5. The first PD frame is located from address 0 to 14 and the 24th PD frame is in locations 345 to 359.

The MD frame is 10 bytes long and is written to the EEPROM every 6 hours. Hence, 40 bytes of data are written to the EEPROM in 24 hours. The first MD frame is located from address 360 to 369 and the 40th MD data frame is located from 390 to 399. The ED data frame is 10 bytes long and is written to the EEPROM every hour. Hence, 240 bytes of data are written to the EEPROM in 24 hours. The first ED frame is located from address 400 to 409 and the 24th ED frame is located from address 630 to 639.

After optimization of the data, collected at the end of 24 hours, the SBD frame which is a maximum of 205 bytes, is written at locations 640 to 844 by module 3. Module 5 then makes an SBD session to the ECC with the data available from those locations in the EEPROM. The address locations from 845 to 979 are reserved for storing any MT message that the FA retrieves, which can be a maximum of 135 bytes. Also, an external EEPROM can be used if more MT messages are envisaged at the FA and if they need to be stored for a longer duration or for any other purposes.

If module 4 notes the emergency-condition information of the inverter status as "true", then the message to alert and inform the ECC of an inverter emergency is pre-written from location 980 to 1023, which then gets sent as an emergency SBD session to the ECC.

2.4 Timing Requirements for Remote Renewable Energy Source SCADA Functions

For complete SCADA functions of RRESs, the communication system should be able to meet the control as well as the data acquisition functionalities. For achieving these functions, the important aspects to consider are the latency of the system as well as data-rate and cost of operation. The cost of operation is minimized by the architectural design and controlled data transmission on a "need to know" basis at the ECC. The response time required for the controlling functions of the RRES, such as "anti-islanding" would be on the order of milliseconds or less. Though Iridium is a LEO system, the SBD service's inherent delays would limit such control capabilities of the ECC. Hence, due to the latency of the system, the developed system is recommended for data telemetry functions and as a redundant communication backup system for the RRES. The details about the time taken for the MO message to reach the VA and MT message to reach the FA are discussed with field test data and theoretical calculations in the next section. It is also seen that the study done before by Margaret [16] on the delay analysis of the SBD services corroborates with the field test data timing analysis.

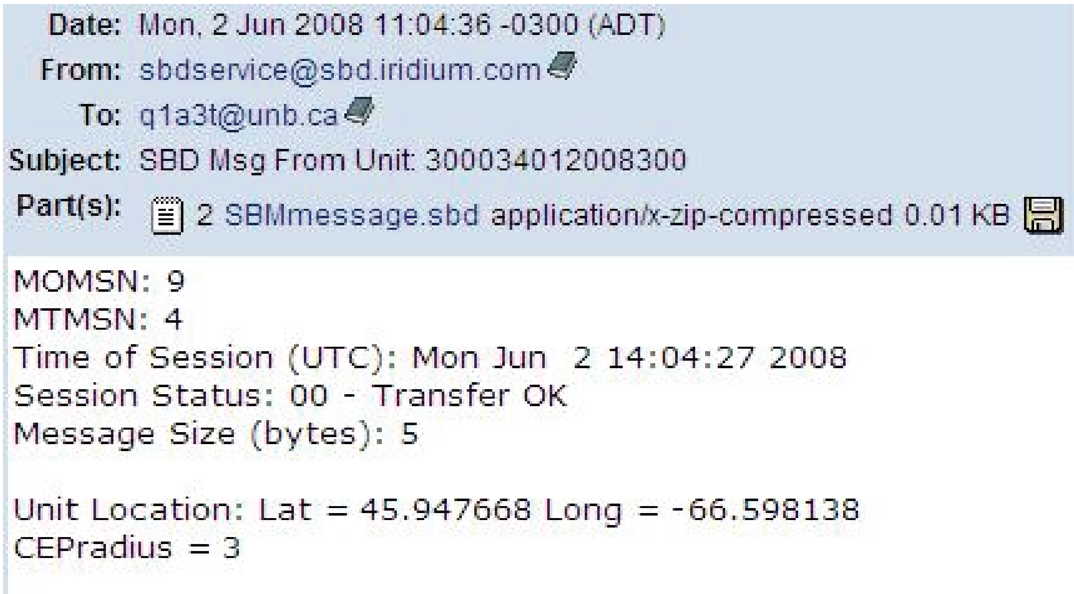
2.5 Developed SBD Communication System's Output

2.5.1 Field Application Testing

The architectural design provides the details of the system that could be implemented in the field. But for testing the FA for data telemetry functions, the data from the inverter/sensors were assumed to be available in the format designed and the same were written in the EEPROM (module 1) as detailed in Figure 2.5. The FA was then implemented to send the MO message (module 5) and receive the MT messages (module 2) depending on the interrupts that were designed at required frequencies and instances. Also, the e-mail addresses at the VA were configured for the MO messages to be delivered. The communication with the transceiver and the PIC with the RS-232 connection was tested and performed as per the requirements. The details of the RS-232 settings and intricacies of setting the PIC and modem to communicate are given in Appendix A.

The developed FA was tested with the MO message “UNB Here” written in the specific location in the EEPROM. The message was received in an e-mail attachment at the VA as in Figure 2.6. The MO Message Sequence Number (MOMSN) and the MT Message Sequence Number (MTMSN) give the number of MO and MT messages sent and received by the particular IMEI. The time stamp of the session is in Coordinated Universal Time (UTC) format where the time for a particular time zone can be expressed as positive or negative offsets from the UTC. The session status confirms the message transfer. The confirmation message also gives the message size and the latitude and longitude position of the ISU where CEP radius means Circular Error Probable, which defines the radius of a circle that represents a 50 percent probability of a position lying in that circle. The geo-location information is only an approximate location of the ISU and if not required in the application, could be disabled.

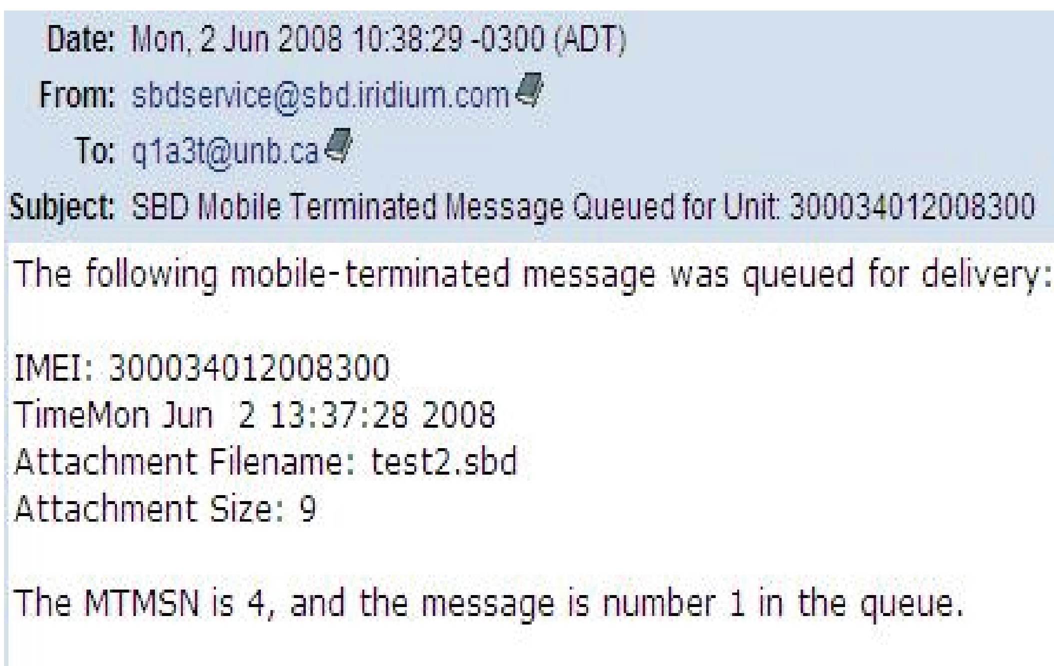
For testing the MT message, an e-mail with the attachment content “Hello UNB” was sent to the ESS from the VA. The confirmation message of its storage in the ESS for polling by the ISU was received as in Figure 2.7. The same message was retrieved at the FA with implementation of module 2 as shown in Figure 2.8. Various information, including the count of MT messages queued at the ESS, are obtained as indicated by the last digit returned by the ATC command SBDI, which is for initiating the SBD session.


Date: Mon, 2 Jun 2008 11:04:36 -0300 (ADT)
From: sbdservice@sbd.iridium.com
To: q1a3t@unb.ca
Subject: SBD Msg From Unit: 300034012008300
Part(s): 2 SBMmessage.sbd application/x-zip-compressed 0.01 KB

MOMSN: 9
MTMSN: 4
Time of Session (UTC): Mon Jun 2 14:04:27 2008
Session Status: 00 - Transfer OK
Message Size (bytes): 5

Unit Location: Lat = 45.947668 Long = -66.598138
CEPradius = 3

Figure 2.6: Mobile Originated e-mail message received at Vendor Application


Date: Mon, 2 Jun 2008 10:38:29 -0300 (ADT)
From: sbdservice@sbd.iridium.com
To: q1a3t@unb.ca
Subject: SBD Mobile Terminated Message Queued for Unit: 300034012008300

The following mobile-terminated message was queued for delivery:

IMEI: 300034012008300
TimeMon Jun 2 13:37:28 2008
Attachment Filename: test2.sbd
Attachment Size: 9

The MTMSN is 4, and the message is number 1 in the queue.

Figure 2.7: Confirmation of Mobile-terminated message queued at ESS

Figure 2.8: Mobile-terminated message received at FA

2.5.2 SBD Service's Delay Time Analysis

The total delay depends on the transmission and propagation delays and the performance of the routing algorithm implemented in the satellites. The various components of the delays associated with the SBD services can be classified into five categories, modem processing time or transmission delay (depending on message size), uplink delay, inter-satellite handoff and queuing delays, downlink delay and e-mail delays.

The modem processing delay for a 205 byte message using an average throughput of 2.4 kbps is calculated to be 683.3 ms. Using the signal travel speed of $3x10^8$ m/s and distance to the satellite and back as approximately 1600 km, the uplink and downlink delay works out to be 5.2 ms. The general queuing algorithms in the satellite nodes suggest that the maximum delays associated with queuing would be on the order of a few hundred microseconds [15], which here is taken as 300 µs giving 1.2 ms in total assuming 4 inter-satellite handoffs. Also, assuming a maximum of 4 inter-satellite handoffs and taking the distance between the satellites as 400 km, it gives an inter-satellite handoff delay of about 5.2 ms. Hence, combining all these delays (683.3 ms + 5.2 ms + 5.3 ms +1.2 ms) only gives 695.0 ms (0.70 s) of theoretical delay.

The timing stamps when deciphered from the e-mail received from the field test at the VA are summarized in Table 2.2.

Table 2.2: Mobile Originated message timings

MO message sent (UTC)	MO message received (UTC)	Difference (s)
18:43:47	18:44:05	18

It is seen that it took 18 s for the MO message to reach the VA from the FA, which corroborates well with the timing for the MO message study done by Margaret [16]. Since, the total delay without the e-mail delay was calculated as 0.7 s, about 99% of the delay time is attributed here for the e-mail delays from the Iridium gateway to the VA.

As the Iridium gateway has an inherent process running once only every 30 s [16] to collect the MT SBD message to queue it for the individual mobile device, the worst case latency for the MT message to reach the ISU could be 30 s plus the other associated delays of about 1 s. Hence, critical control applications like anti-islanding of the DG sites may not be possible as the responses that are required at the field for such operations are in the order of milliseconds or less.

2.6 Conclusion

Controlled MO and MT messages were sent and received at the field with the implementation of the various modules. The code written in the CCS C compiler for testing the system is given in Appendix B. Appendix B also contains a picture of the system implemented, showing the PIC8722, RS-232 connections, 9601 transceiver, cables, lightning arrestor and the antenna. With the system implemented and the test results as given in section 2.5.1, the latency of the system was calculated and analyzed.

Certain tests where MO message transmission failed in its first couple of trials when the SBD service of ISS was not able to communicate to the satellite, even though the transceiver showed availability of satellite signal, were observed. This case was considered in the design, where the FA keeps trying till the MO message until transmission is successful. The test results with the transceiver responses and their explanations are given at Appendix B.

Chapter 3

3. Effective Use of Limited Communication

3.1 Requirement of SBD Frame Optimization and Non Linear Programming for Solution

DG formulated with RRESs and most predominantly wind power energy has achieved a predominant place as a driver in the green energy market [18]. Efficient operation of these wind turbines with huge investment of approximately US$ 1000 per kW warrants efficient, optimized and intelligent communication system design for proper maintenance of the system. This would also help for the reliability of power as well to reduce the cost of maintenance over the years. The main objective of optimizing the SBD frame for the data telemetry function of a DG is to make the:

i. Short Burst Data service of Iridium System viable and competitive, and
ii. communication system intelligent.

The Iridium communication system for the data telemetry of DG generally comes into contention when there are practically no other forms of communication at the site or for backup systems. But for low data volumes it could actually be less expensive than the alternatives. Hence, the SBD service of Iridium is analyzed as a potential contender for monitoring the remote DG even when other communication facilities are available. To achieve this, the system and data requirements at the ECC have to be studied and implemented considering the constraints of the limited resources and cost of Iridium's SBD service. Hence, the challenge is to maximize the data transfer and most importantly the required data is transferred vis-à-vis the cost incurred for the same.

Not all the physical data available can be collected at the field, nor can all the collected data be transmitted or need to be transmitted to the ECC. Hence, specific application development criteria are formalized and a specific design is done, to make the SBD service of Iridium viable as a communication system for the data telemetry functions of DG.

The SBD service of Iridium has a maximum of 205 bytes for MO messages and a maximum of 135 bytes for MT messages. Hence, optimization of these 205 bytes of MO message per session is done so that there is maximum utilization of the capacity per session as well as the most relevant and required data is communicated to the ECC. The tool used here for achieving this is NLP. NLP can be applied to various fields of study. It is most extensively used in business and economic situations, but can also be utilized for engineering problems. Some industries that use NLP include transportation, energy, telecommunications, and manufacturing [19].

Hence, 205 bytes of data from the data collected over the 24-hour period contend to fill the SBD frame. Basically, the goal is to pack the SBD frame with the most optimized data sub-frames from amongst PD, MD and ED as the cost per session of SBD or per kilobyte of data via SBD service is relatively high.

3.2 Developing the Non Linear Program Problem

The basic steps involved in developing the NLP problem are to decide on the decision variables, the objective function and the constraints. A mathematical model is formulated which when solved gives the most optimized solution for packing the limited resource, the SBD frame. Here, the solution tries to maximize the "data byte transfer" function (objective function) by solving the number of various data sub-frames (decision variables) subject to certain constraints to fill the 205 bytes of the SBD frame.

The rational behind the choice of the decision variables, the basis and development of the objective functions and the constraints are described and formulated in the sections to follow.

3.2.1 Developing Decision Variables

In modeling the NLP, the decision variables are chosen such that, solving it, completely gives the solution needed to solve the problem in question. From the perspective of the data requirement at the ECC for monitoring and control of an RRES, the data at the field were categorized into three types as, PD, MD and ED. The detail contained in one frame of PD, MD and ED was shown in Figure 2.4 in Chapter 2. Hence, the decision variables considered here are the sub-frames, 5 bytes long, of the PD as N_{pg}, MD as N_{mi} and ED as N_{ei}. The output expected of the optimization process is the optimal solution regarding the number of sub-frames amongst the decision variables that would fill the MO SBD frame at the end of 24 hours for an SBD session. There are 41 sub-frames, as the maximum MO SBD frame length is 205 bytes.

3.2.2 Developing Constraints

In developing an intelligent and also optimized communication system for the RRES with the SBD service of Iridium, the system should be able to pick the data that is most needed to be sent to the ECC depending on the behavior of the RRES system. To choose between the decision variables to fill the SBD frame, it should be constrained by the physical behavior of the system such that the data sent not only gives the value but also describes the system. Hence, keeping this as the fundamental requirement of the system, the constraints developed are the:

i. data byte size constraint, and
ii. Power, Maintenance and Environmental (PME) data constraint.

3.2.2.1 Data Byte Size Constraint

The first constraint on the system is that the number of sub-frames of the decision variables cannot be more than 41 as a sub-frame is designed to be 5 bytes long with a maximum SBD size frame being 205 bytes per session. Inequality (3.1) expresses the data byte size constraint mathematically:

$$N_{pg} + N_{mi} + N_{ei} \leq 41 \qquad (3.1)$$

Also, the value of N_{pg} , N_{mi} and N_{ei} should be integers, greater than or equal to zero. Hence, Inequality (3.2) gives the other constraint mathematically as:

$$N_{pg} \geq 0$$

$$N_{mi} \geq 0 \qquad (3.2)$$

$$N_{ei} \geq 0$$

3.2.2.2 PME Constraint

The growth of wind power energy systems for green power has also caused the appearance of many reliability issues mainly related to maintenance practices [18]. This opens up the area for communication systems which can help mitigate the failures of the turbines as well as for proper maintenance at the field by intelligent data telemetry systems design. A system capable of adjusting/selecting the data at the field depending on the ever changing and unpredictable conditions in the field, which validate the foreseen or indicate the unforeseen maintenance requirements, can improve the maintenance practices and mitigate the reliability issues. Hence, the PME data constraint tries to achieve this by optimizing the SBD frame with MD sub-frames depending on PD and ED data patterns recorded.

One of the main issues with wind power generation is to maintain the generator rpm constant to maintain the power frequency with the changing load and wind velocity. As the generator shaft is coupled with the shaft of the wind turbine, whose speed varies with the speed of the wind, a gear box is generally used to regulate the change of wind turbine speed so that a constant rpm is maintained in the generator shaft. Hence, the gear needs to maintain the speed of the generator shaft constant to the changing wind speed patterns subjecting the gear to continuous work. This changing environment in the gear box could affect the gear, its bearings and most importantly the lubricant, and proper maintenance needs to be done depending on how the wind turbine is being operated. Hence, data about the lubricant conditions could be communicated to the ECC depending on how the gear is being operated.

The suitable operation of the wind turbine mainly depends on the behavior of the gearbox containing planetary gears and bearings, requiring special attention due to its extreme operating conditions. Hence, the lubricant and wear particles analysis is considered to be the most efficient and predictive/proactive tool to obtain an optimum performance of the wind turbines. The problems related to the maintenance of the turbine through the lubricant analysis based on the experience achieved by the International Wearcheck Group suggest that the main issue is the micropitting due to lubricant choices, apart from others [18]. Wearcheck is a group of independent laboratories, spanning the Earth, dedicated to oil and wear particle analysis.

Micropitting is a surface fatigue phenomenon mainly observed in gears. Choice of lubricant and surface roughness are the key factors leading to micropitting. To prevent micropitting the lubricant thickness should be maximized and temperature is fundamental for the thickness of the lubricant. Hence, monitoring the lubricant condition becomes critical. Basically, the resistance to micropitting decreases when temperature in the gears increases. The equilibrium temperature of the lubricant is established between the heat dissipated in the system by conduction and convection vis-à-vis the heat generated by friction which depends on the work done by the gears [18], increasing with higher power generation and the ambient temperature and humidity increase of the surroundings.

Hence, under the PME constraint, three regions of operation (PME1, PME2, PME3) of the system are visualized and developed to decide on the number of sub-frames to fill the SBD MO message amongst PD, MD and ED. Figure 3.1 explains the regions of operation of the system. Depending on the change of power output (kW) or turbine speed (rpm) over the day (signifying values of PD being higher/lower/rated which indirectly is responsible for increased/decreased temperature of the lubricant by friction) and ambient temperature and humidity changes (signifying values of ED which has effect on the maintenance parameters of the lubricant), the sub-frames N_{pg}, N_{mi} and N_{ei} are decided to fill the MO SBD message. The system should be sensitive to reporting relatively more N_{mi} sub-frames in the MO message on a more regular basis if the system has operated in region PME3 (i.e. power output or turbine speed over the day is higher than the optimal operational values or if the ambient temperature or humidity data collected over the day is higher than nominal), which should be the case as this may lead to a temperature increase of the lubricant leading to micropitting of the gears. Also, if the system has operated in region PME1 over the day (i.e. the power output or turbine speed over the day is lower than the rated values for a long time) the N_{mi} sub-frames should again be reported relatively higher in the MO SBD message as this may not be a suitable environment for the high performance self lubricating bearings to function at their maximum efficiency.

Also, if the system operated in region PME2 over the day (i.e. the power output or turbine speed over a day is generally running on a rated level and the ambient temperature around normal conditions), the MO message could have relatively less N_{mi} sub-frames as the data required for the maintenance is presumed to be relatively low for such a situation and hence can have, as designed, balanced sub-frames of N_{pg}, N_{mi} and N_{ei}.

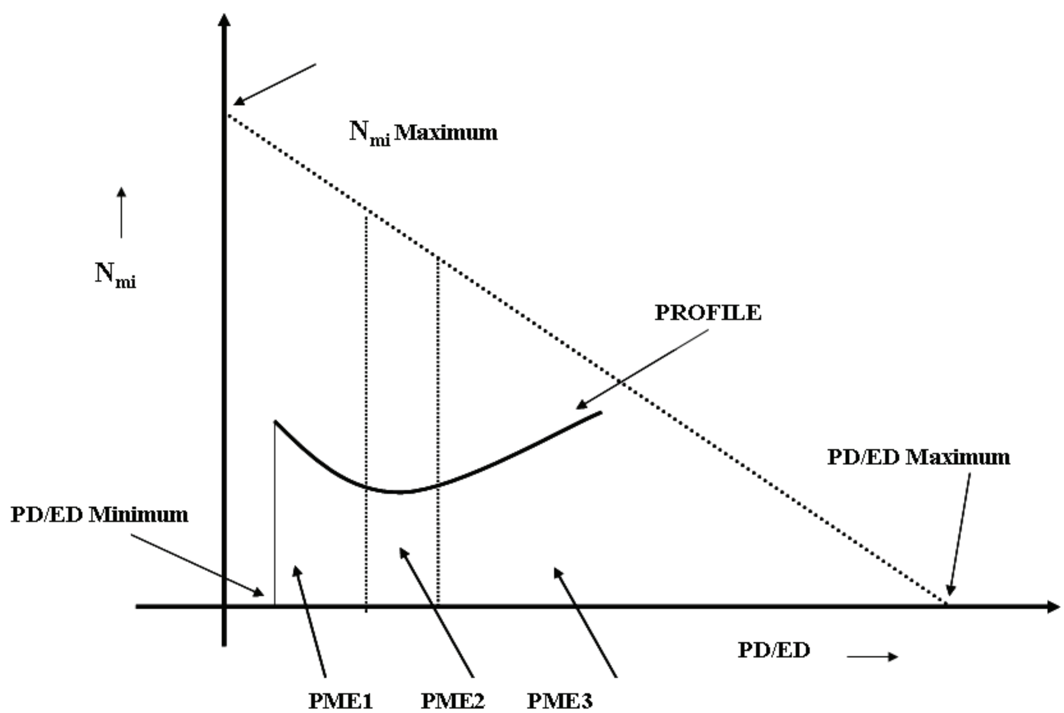


Figure 3.1: Turbine’s region of operation (Modeling the physical behavior of system)

Taking the number of sub-frames for each to fill the SBD frame, depending on the operation of the system in the three specified regions, would give the optimized and significant MO SBD data frame to be communicated to the ECC with the low-cost criteria of operating the Iridium SBD service for data telemetry of the RRES.

The PME constraint is mathematically derived as follows:

The profile for deciding the N_{pg}, N_{mi} and N_{ei} sub-frames from the values of PD and ED collected over a day is conceptualized as a parabola of the shape shown in Figure 3.1. The three distinct regions are when the wind speed, power output and ambient temperature are lower than the rated range (PME1), the region where the wind speed, power output and ambient temperature are consistent with the rated range (PME2) and when wind speed, power output and ambient temperature are relatively higher (PME3) consistently. How the values of PD and ED collected over the day influence the number of sub-frames (N_{pg}, N_{mi} and N_{ei}) contending to fill the SBD frame is described mathematically below.

The general form of a parabola is given by:

$$y = a(x - h)^2 + K \tag{3.3}$$

where, y are the ordinates, x are the abscissa values, a is the second-order constant, and h and K are the coordinates of the vertex of the parabola.

Equation (3.3) applied to the variables here which gives the PME constraint as:

$$N_{mi} \geq K_1 \left(N_{pg} - \frac{K_2 - N_{ei}}{K_4} \right)^2 + K_3 \tag{3.4}$$

where, K_1, K_2, K_3, and K_4 are the quadratic constant, scaled offset, offset and offset scalar respectively, which are chosen so that the profile of the curve represents what N_{pg}, N_{mi} and N_{ei} would be reasonable at various conditions of PD and ED values collected over the day. Also, to make the system responsive and sensitive to the number of sub-frames of MD, the PME constraints could be automatically changed over a year, considered as the regular maintenance period. The logic is that, more N_{mi} are included for the six months after the regular maintenance period. For the next six months, N_{mi} data could be reduced, relative to the first six months as the ECC has the confidence from the data of the N_{mi} from first six months as well as the next regular maintenance schedule would be approaching soon.

Two PME constraint equations developed here are for the first and the second half of the regular maintenance period. On substituting the values of the constants in Inequality (3.4), the two constraints become:

$$N_{mi} \geq \frac{10}{20^2}\left(N_{pg} - \frac{80 - N_{ei}}{4}\right)^2 + 10 \tag{3.5}$$

$$N_{mi} \geq \frac{10}{35^2}\left(N_{pg} - \frac{140 - N_{ei}}{4}\right)^2 + 2 \tag{3.6}$$

Inequality (3.5) is designed for the first half after the regular maintenance period where monitoring of the RRES's MD occurs more frequently. Hence, K_3 is given a value of 10.

Inequality (3.6) is for the second half where relatively less MD is presumed to be required at the ECC. Hence, K_3 is given a value of 2.

3.2.2.3 Plotting the Constraints

The data byte size constraint given by Inequalities (3.1) and (3.2) is shown in Figure 3.2. The PME constraints given by Inequalities (3.5) and (3.6) (for N_{ei} of 1 and 41) is shown in Figure 3.3 and 3.4 respectively. Both these constraints plotted together (Inequalities (3.1) and (3.2) and Inequality (3.5)), for N_{ei} =1 and 41, give the solution points (N_{pg}, N_{mi}, N_{ei}) under the area carved by the parabola and the triangular plane as in Figure 3.5.

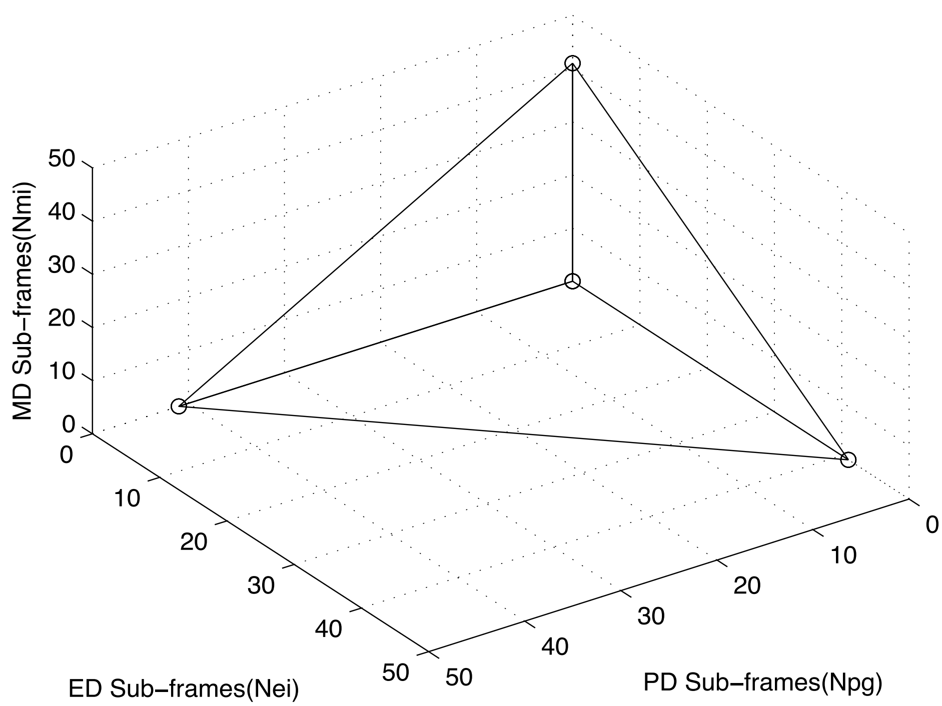


Figure 3.2: Data byte constraint

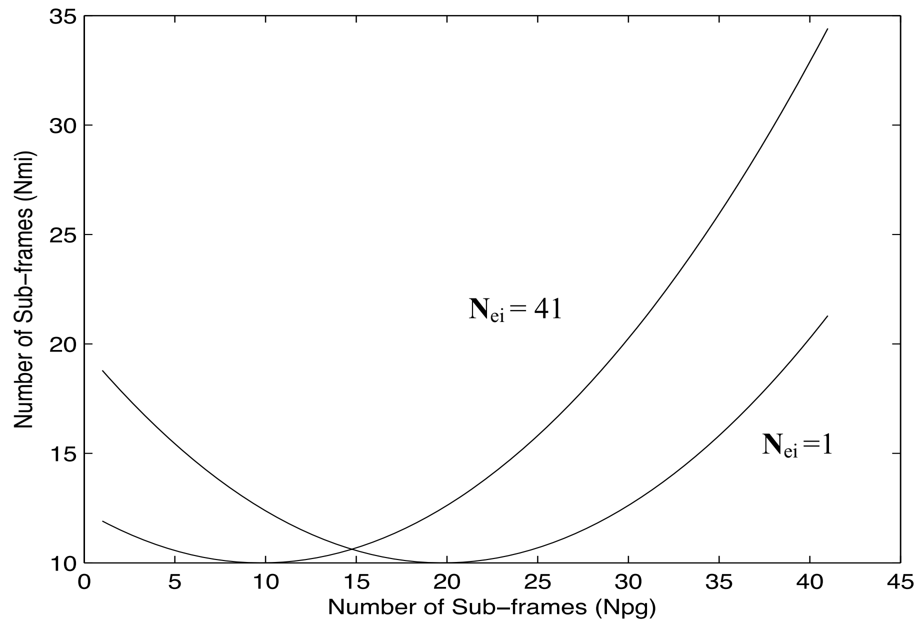


Figure 3.3: Power Maintenance Environmental constraint with Inequality (3.5)

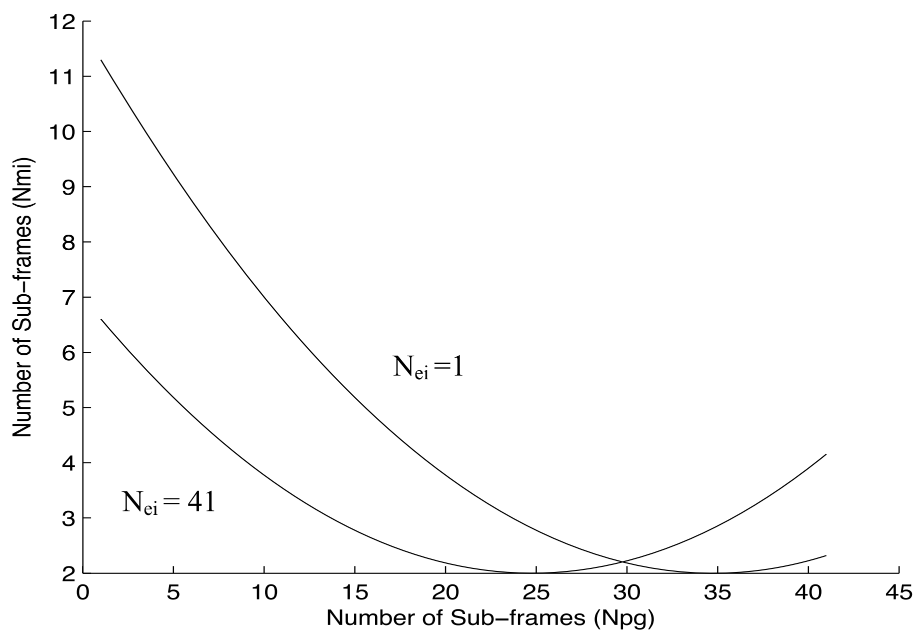


Figure 3.4: Power Maintenance Environmental constraint with Inequality (3.6)

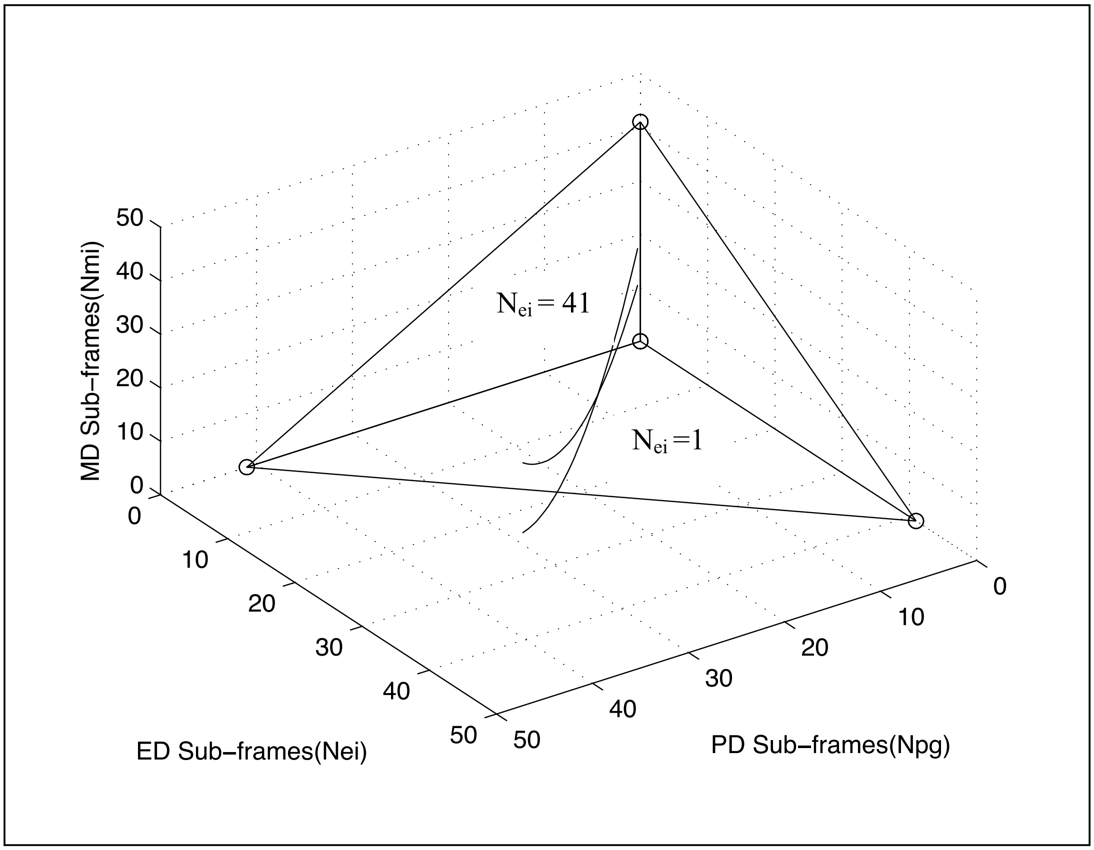


Figure 3.5: Data byte and PME constraints

3.2.3 Developing Objective Function

The objective of developing the optimization problem with the decision variables and the constraints which here happen to be a non-linear optimization is to maximize the profit by communicating the most-needed data to the ECC and at the same time making the system intelligent in this data-constrained environment using the Iridium SBD service. The profit at the ECC is conceived by the optimized transferred MO SBD data giving more value for monitoring purposes, planning purposes or for maintenance scheduling.

Hence, after the constraints are solved to get the feasible region, which is the set of points satisfying all the constraints, the solution (N_{pg}, N_{mi} and N_{ei}) is fed to the objective function to verify which of the solutions give the maximum profit. Thus, the objective function is developed to maximize the profit which mathematically is given by equation (3.7).

$$R = A\,N_{pg} + B\,N_{mi} + C\,N_{ei} \tag{3.7}$$

The coefficients A, B and C are chosen to provide appropriate weights for the number of sub-frames (N_{pg}, N_{mi} and N_{ei}), and indicate which data has more significance to maximize the profit at the ECC. Also, to make the system adaptive over the summer and winter months of the year, the coefficients A, B and C of the objective function can be varied to give appropriate weights to the sub-frames for maximizing the profit depending on the conditions on the field. During the summer months when the temperature and humidity may increase, the constant A could be reduced and B and C relatively increased so that more weight is on the N_{mi} and N_{ei} frames. On the contrary, during winter months the objective function could be changed to reflect more PD as the environmental conditions are assumed to be more suitable for functioning of the RRES generators and turbines. The coefficient choices and changes could also be on the discretion of the person working at the ECC depending on the data requirements at the ECC. The objective function considered here is with A, B and C as 50, 30 and 10 respectively, which makes Equation (3.8) as:

$$R = 50\ N_{pg} + 30\ N_{mi} + 10\ N_{ei} \tag{3.8}$$

The optimal solution of the problem for maximization of the profit is the point in the feasible region which has the largest objective function (R) value. Depending on different values of R calculated from the points in the feasible region, the solution which gives the largest value of R is chosen as the most optimized sub-frame sizes. Hence, those values of sub-frame sizes make the optimized MO SBD data frame to be transmitted to the ECC at the end of every 24-hour period.

3.3 Non-Linear Programming Implementation

The optimization problem is tested and solved in MATLAB® using an exhaustive search method and the results are compared with the solution given by the built-in functions in MATLAB® to solve an NLP. Finally, this logic is coded in the PIC using the CCS C for implementation of the NLP, as conceived in Chapter 2 in the state diagram (Figure 2.3) as module 3. The PIC could be programmed for automatic switching of the constraint and objective functions depending on the scheduled maintenance timeline, winter and summer conditions as described in section above. This could be made possible by either an MT message from the ECC or could be done manually during the scheduled maintenance period.

3.3.1 Non-Linear Programming Solution in MATLAB® and PIC

Developing an exhaustive search algorithm requires searching all the combinations of N_{pg}, N_{mi} and N_{ei} values within the space of 1 to 41 bytes, which satisfy the constraints. This is then put into the objective function and the combination which gives the highest value of Equation (3.7) is selected as the optimized result. Hence, to get an estimate of the problem size, the derivation below gives the total number of combination points that the search algorithm has to run through for the result.

Considering 41 cases where one of the decision variables varies from 1 to 41, the general form for the total number of combinations of N_{pg}, N_{mi} and N_{ei} is as follows:

$$S = \frac{(1)(2)}{2} + \frac{(2)(3)}{2} + \frac{(3)(4)}{2} + ... + \frac{(40)(41)}{2} + \frac{(41)(42)}{2} \tag{3.9}$$

This can be written as:

$$S = \frac{1}{2}\sum_{i=1}^{41} i\,(i+1) \tag{3.10}$$

$$S = \frac{1}{2}\sum_{i=1}^{41} i^2 + \frac{1}{2}\sum_{i=1}^{41} i \tag{3.11}$$

Expanding and solving we get:

$$S = \frac{1}{6}\left[i^3 + 3i^2 + 2i \right] \quad [20] \tag{3.12}$$

Substituting, i = 41, we get S = 12,341 combination points that the algorithm has to search. The exhaustive search algorithm solves for all the points satisfying the constraints. Figure 3.6 shows the variability of values of the sub-frames (N_{pg}, N_{mi} and N_{ei}) satisfying the constraints, depicting that the sub-frame combination is sensitive to the system working either in regions PME1, PME2 or PME3, as solved by the exhaustive search algorithm. Figure 3.6 is plotted for selected samples of the solution points, but also containing the solution with the highest value of the objective function given by the exhaustive search algorithm. Figure 3.6 also shows the solution points of N_{pg}, N_{mi} and N_{ei} as 39, 1 and 1 respectively, with the maximum value of the objective function amongst all the solution points. The graph is plotted for constraints Inequality (3.1), Inequality (3.2) and Inequality (3.5) and the objective function Equation (3.8). For testing the variability of the optimized solution output for various values of the objective function coefficients (A, B and C) are as tabulated in Table 3.1. The code for the exhaustive search algorithm for solving the developed NLP is attached in Appendix C and the execution time of the same in MATLAB® is 1.39 s.

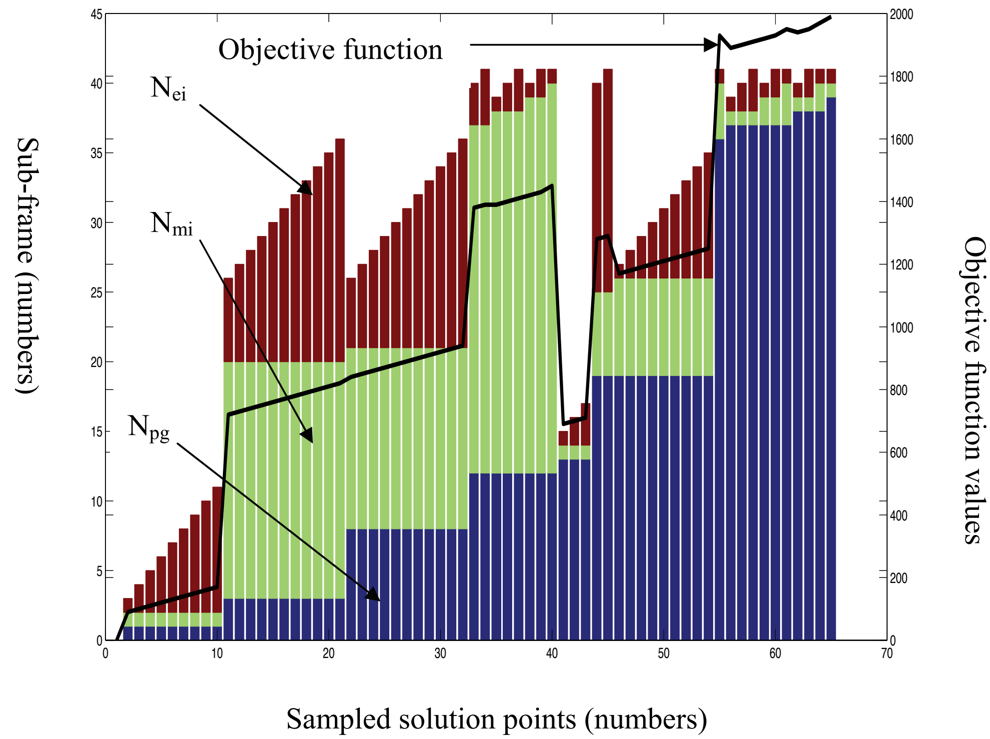


Figure 3.6: Optimized solution graph

Also, MATLAB® has built-in functions to solve the NLP problems. This nonlinear inequality constrained problem is solved by the "fmincon" function which basically solves the objective function with all the solution points satisfying the constraint and gives the point solution which has the highest value of the objective function. The three basic steps to solving an NLP with this function are as follows [21]:

Step 1: Write an m-file for the objective function,

Step 2: Write an m-file for the constraints, and

Step 3: Invoke constrained optimization routine.

It was seen that the results from the exhaustive search algorithm and from the built-in function validate each other. The code with the built-in function of MATLAB® to solve the NLP is attached in Appendix C, where the inequalities have been solved and used in the code due to the requirement of a certain format of the inequalities by the built-in functions.

Table 3.1: Optimization results

Objective Function Coefficients			**Results**			
A	B	C	N_{pg}	N_{mi}	N_{ei}	R
50	30	10	39	1	1	1990
50	50	50	15	13	13	410
10	50	30	1	39	1	1990
30	10	50	1	1	39	1990

The optimized solution output can be changed either by changing the objective function or by changing the constraints. The coefficients of the objective function can be automatically changed with MT messages by experienced personnel at the ECC and also the constraints could be changed depending on the requirements. It is seen that for the constraints designed, the solution is optimized at different values of N_{pg} N_{mi} and N_{ei} by changing the ratio of the coefficients A, B and C of the objective function.

The exhaustive search algorithm can be implemented in the PIC and the optimum sub-frame size of N_{pg}, N_{mi} and N_{ei} calculated at the end of the every 24-hour period. These values are then used to pick the number of sub-frames of PD, MD and ED (data collected over the 24-hour period whose frequency and size and location in EEPROM are as described in Chapter 2) to make up the optimized SBD frame for communication.

Also, depending on the message requirement and the operating budget, more SBD sessions could be initiated in a day and hence optimization of 82 sub-frames or 123 sub-frames for 2 and 3 SBD sessions respectively or more could also be done. The PIC8722 has a 5 ns clock, 128 kilobytes of program memory and 3936 bytes of data memory. Allocating one third of the data memory (1312 bytes) would allow a maximum matrix size of 36 by 36 to be solved. Implementing the exhaustive search algorithm on the PIC8722 for 1 SBD frame optimization would have 3 operations to calculate the PME constraint matrix, 15 operations to calculate for comparing the constraints, 1 operation to calculate the R value and 1 operation each for loop iteration. This would give a total of 1,380,142 operations with N_{pg}, N_{mi} and N_{ei} of 1 to 41. Also, the total number of operations for the algorithm with 2 SBD frame (82 sub-frames) would be 11,034,166.

Chapter 4

4. Cost and Alternative System Comparison with Iridium SBD Service for RRES SCADA Functions

4.1 Introduction

Gagliarducci et al. [26] discusses GSM-based monitoring and control of photovoltaic power generation, where GSM stands for Global System for Mobile communications. Though this could be cost effective, its availability still is an issue for remote DG. Hence, the systems taken into consideration for comparison are based on their setup cost being low when the DG sites are in remote locations and also, other conventional communication systems such as GSM, wireless standards, internet, and optical fibers, are not available or some are too expensive as an upfront investment.

The three systems of communication compared are:

i. the Short Burst Data Service of Iridium Satellite System,
ii. Armature Radio, and
iii. Cellular Radio.

The choice for a particular type of communication system for RRES monitoring depends largely on the specific application and its requirements but at the same time budget and available technology are the other factors which influence the decision. Depending on the data volume requirements by the application, the SBD service of Iridium could prove to be more effective and a financially prudent decision as the hardware cost of the SBD modem and it accessories is low. Also, remoteness and unavailability of any other communication alternatives or at times of failure of the primary communication system, qualifies the Iridium satellite communication system as a contender for a data telemetry system. Hence, this chapter compares the various options considered to be viable for the data telemetry of RRES taking into consideration the application requirements on data volumes and the associated installation and monthly cost.

In April 2006, the U.S. Department of Defense (DoD), Defense Information Systems Agency (DISA) awarded Iridium a contract for commercial mobile satellite services for voice, data, and paging, utilizing the Iridium satellite constellation. Through this DISA contract, Iridium was also approved to provide the 9601 transceiver to the U.S. DoD, and other government users. The 9601 transceiver meets broads requirements among users in defense, and homeland security, implementing the standard in support of logistics, force tracking, remote sensing and other data exchange applications. Also, Iridium plans to deploy its next generation 'Iridium Next' satellite constellation within the next seven years and is investing about US$2 billion to construct and deploy this new network [22]. Hence, with the U.S. DoD utilizing the 9601 SBD service and the increase in the economy of scale of the business, the SBD service cost as well as the hardware cost could decrease further with time.

The following sections of the chapter discuss the three compared systems with the perspective of setting it as a data telemetry function for RRES.

4.2 Comparison of Various Communication Systems

4.2.1 SBD Service of Iridium Satellite System

The ISS offers various services such as voice, short messaging service (SMS), SBD, and paging. For data telemetry of DG, the SBD services of Iridium seem viable due to their low hardware cost as well as the billing being as per usage. A low-cost architecture was developed and optimization of data bytes done for communication in a constrained environment since only 205 bytes of data per session is supported by the 9601 SBD transceiver and also the service cost depends on the data bytes sent over the network.

SBD is a data communication service of Iridium, where an application can send and receive short data messages ranging from 1 to a maximum of 1960 bytes using small transceivers. Hence, the SBD service could be competitive where the data volumes involved are not too large.

Here for comparison, a low data volume is considered to be one MO SBD session and one MT SBD check initiated in a 24-hour period. For a low data volume the total MO message size per month would be 6150 bytes (taking a maximum of 205 bytes/MO message) and MT message would be 4050 bytes (taking a maximum of 135 bytes/MT message) which would cost CAD 12.01 and CAD 7.91 respectively with a rate of CAD 2 per kilobyte. A large data volume is considered where 24 MO SBD sessions and 24 MT SBD checks are initiated in a 24-hour period. Hence, for a large data volume the total MO message per month would be 147600 bytes and total MT message would be 97200 bytes which would cost CAD 288.3 and CAD 189.9 respectively taking a rate of CAD 2 per kilobyte. A comparative tabulation of cost per data volume per month, setup cost as well as the advantages and disadvantages of the three compared communication systems for DG telemetry application is given in Table 4.1.

4.2.2 Amateur Radio

AR frequency allocation is done by National Telecommunications Authorities and globally the International Telecommunication Union (ITU) oversees how much radio spectrum is set aside for AR transmissions. ITU in its International Radio Regulations, divides the world into three ITU regions for the purposes of managing the global radio spectrum. Radio amateurs can use the AR for a variety of transmission modes, including Morse code, data, and voice. Specific frequency allocations vary from country to country and between ITU regions [23]. Canada falls in ITU region II.

The AR may operate from just above the Amplitude Modulation (AM) broadcast band to the microwave region in the gigahertz range, though many AR are found in the frequency range that goes from 1.6 MHz to just above the citizens band (27 MHz) [24].

4.2.3 Point-to-point Radios

The point-to-point RMs operate in the unlicensed Industrial, Scientific and Medical (ISM) frequency band of either 900 MHz or 2.4 GHz solutions. Though operating at 900 MHz yields significantly longer range than what is possible at 2.4 GHz, a 900 MHz radio solution is permissible in fewer countries. Digi RMs [27] claim that their products with an output power of 1 W have a range of 22 km and a 5 km range when the output power is 50 mW. These were recorded using 2.1 dB gain antennas. A Line-of-Sight (LOS) path between transceivers is required for reliable communication.

Hence, setting up point-to-point radios for monitoring of an RRES could be cost effective as once it is setup, no monthly fee needs to be paid and as much data could be transmitted but would have limitations due to the ISM frequency band operation and related interference issues and also the limitation of distance and LOS of the ECC from the RRES site.

4.3 Cost Comparison

Table 4.1: Cost comparison

Communication System	Costs (CAD)		Coverage (km)	Data Volume (Bytes) per month	
	Setup Cost (CAD)	Monthly Cost (CAD)		Low	High
Iridium SBD Service	600	20+2 per kb	Unlimited	6150 (30 MO SBD Sessions), 4050 (30 MT SBD Sessions)	147600 (720 MO SBD Sessions), 97200 (720 MT SBD Sessions)
Amateur Radio	600	---	Limited	Unlimited	Unlimited
Point-to-point Radio	500	---	20	Unlimited	Unlimited

Table 4.1: Cost comparison (continued)

Communication System	Monthly Cost estimate (CAD)		Advantages/Disadvantages/Comments
	Low	High	
Iridium SBD Service	12.01+7.91 (maximum)+20 = 39.92	288.3+189.9 (maximum)+20 = 498.14	i) Service at all locations on the Earth. ii) Comparatively expensive so needs application specific data transfer regulation and data optimization. iii) Message delay basically confines the system for telemetric purpose and not for critical control functions.
Amateur Radio	---	---	i) Operator needs licence to operate. ii) Interference is expected.
Point-to-point Radio	---	---	i) Maximum coverage of 30 km and needs LOS for communication. Hence, if ECC is further than 30 km and if not in LOS then the system has limitations. ii) Operates in unlicenced ISM frequency band so operator does not need licence. iii) Interference due to other systems in the same operating frequency.

4.4 Conclusion

When available, communication systems such as point-to-point radio, internet, and wireless standards, could be more cost effective though they have their limitations of service qualities and distance coverage. Hence, the SBD service of Iridium as seen in Table 4.1 with comparable setup cost and its availability worldwide when designed for low data volume could be a good system for RRES SCADA functions or even for back up systems on failure of primary communication systems.

Chapter 5

5. Conclusion

5.1 Contributions and Recommendations

An overview of DG and the ISS was studied and documented and the necessity of monitoring a DG system formulated with an RRES, for its maintenance and dispatchibility was developed. The SBD service of Iridium was chosen as the communication system for its service availability at all locations of the Earth as well as for its low hardware and setup cost.

A cost-effective interrupt-driven microcontroller architecture was developed for the practical purpose of remote installation and automatic functioning of the communication system. The system with the 9601 SBD Iridium transceiver was developed and tested for MO and MT messages and the timing and delay analysis of the Iridium SBD service was analyzed. It was seen that the MO message has a delay of about 18 s attributed mostly to the e-mail delays. The MT message had an inherent SBD service delay of 30 s and hence, the minimum time to retrieve an MT message at the FA would be 30 s plus the associated delays of uplink and downlink at the FA.

With this delay of MT messages, it is seen that critical control functions such as anti-islanding of the inverter cannot be achieved by this system but could be used as a backup system. Also, the functions of monitoring the RRES can be well met by the SBD services of Iridium.

This thesis also researched into the idea of optimizing the 205 bytes of the SBD data packet for cost effectiveness and limiting the data to a "need to know" basis at the ECC and also for making the communication system intelligent. An algorithm was developed taking into consideration the requirements of data at the ECC and the mechanics of the RRES and wind turbine in particular. This was solved using NLP and an optimized set of bytes for the PD, MD and ED, from the data acquired over the day, to fill the 205 bytes of SBD message, was calculated.

Finally, the thesis looked into other communication systems for RRES monitoring and compared the cost and the advantages and disadvantages of each. It is seen that for low data volumes, the SBD service with an intelligent microcontroller-based architecture and optimization of the SBD packets would prove to be a good system for RRES monitoring or as a backup system and especially so as its service is available where conventional communication services are not.

5.2 Future Work

This thesis developed the architecture and implemented the interrupt driven microcontroller system for testing the SBD service of Iridium for the MO and MT messages and also developed the algorithm for optimizing the SBD data bytes.

For taking the research into practical implementation, work towards interconnecting the system to the inverter and sensors and collecting the data in the EEPROM from the field, as discussed in Chapter 2, could be done. The optimization algorithm discussed, developed and tested in MATLAB® could be implemented in the PIC microcontroller so that the complete architecture conceived in Chapter 2 could be realized. After optimization, for the algorithm to choose and make the SBD frame from amongst the PD, ED and MD frames from the EEPROM, it could look into the data pattern and decide on which to choose, depending on the differential data amongst PD, ED and MD collected over the day. Also, at the VA, a smart application with the programming language C# or with any other high-level programming languages can be developed for retrieving the MO messages from the e-mail attachments and logged into the database automatically and periodically.

The MO and MT message delays were mostly due to the processes at the gateway and the e-mail delays. Hence, for lower MO message delays and the possibility of using the system for critical control applications, this research could be taken further by testing the system with SBD service between two ISUs as opposed to ISU and e-mail.

References

[1] J. Meng and S. Barnes, “Distributed generation communications utilizing a real-time FPGA-based channel simulator in the ISM frequency band”, *International Journal of Emerging Electric Power Systems*, vol. 8, no. 1, p. 3, 2007.

[2] L. Chang, “Wind energy conversion systems” *IEEE Canadian Review*, Spring, no. 40, pp. 12-16, 2002.

[3] Y. Xue, L. Chang, and J. Meng, “Dispatchable distributed generation network - A new concept to advance DG technologies,” *IEEE Power Engineering Society General Meeting*, pp. 1-5, June 28, 2007.

[4] R. Hobby, “An introduction to the iridium(R) system,” in *Communication Opportunities Offered by Advanced Satellite Systems - Day 1 (Ref. no. 1998/484), IEE Colloquium,* (London, UK), pp. 1/1-110, Oct. 13, 1998.

[5] Company Profile. (2007). Retrieved October, 2007, from www.iridium.com http://www.iridium.com/about/history.htm

[6] J. D. Ware, M. Grund, S. P. Liberatore, P. A. Koski, and, S. M. Faluotico, “A solar powered ocean observatory using acoustic and Iridium links,” in *Oceans, 2005, Proceedings of Marine Technology Society(MTS)/IEEE*, (Washington DC, USA), vol. 2, pp. 1565-1571, Sept. 17-23, 2005.

[7] D. J. Marihart, “Communications technology guidelines for EMS/SCADA systems,” *Power Delivery, IEEE Transactions*, vol. 16, pp. 181-188, Apr. 2001.

[8] IEEE guide for monitoring, information exchange, and control of distributed resources interconnected with electric power systems. *IEEE Standard. 1547*, pp. 1-158, Mar. 2007.

[9] J. Yin, L. Chang, and C. Diduch, "Recent developments in islanding detection for distributed power generation," in *Power Engineering, 2004, LESCOPE-04, Large Engineering Systems Conference,* (Halifax, Nova Scotia, Canada), pp. 124-128, July 28-30, 2004.

[10] H. Keller, and H. Salzwedel, "Link strategy for the mobile satellite system Iridium," in *Vehicular Technology Conference, 1996. 'Mobile Technology for the Human Race', IEEE 46th*, (Atlanta, Georgia, USA), vol. 2, pp. 1220-1224, Apr. 26-May 1, 1996.

[11] Implementation Manual for IRIDIUM Satellite Communications Service (Draft v1.0 ed.), Feb. 15, 2006.

[12] C. E. Fossa, R. A. Raines, G. H. Gunsch, and M. A. Temple, "An overview of the IRIDIUM (R) low Earth orbit (LEO) satellite system," in *Proceedings of the IEEE 1998 National Aerospace and Electronics Conference NAECON 1998,* (Dayton, Ohio, USA), pp. 152-159, July 13-17, 1998.

[13] Iridium SBD Service Developers Guide (Release 1.2 ed.), Feb. 2006.

[14] IRIDIUM 9601 SBD Transceiver Product Developers Guide (Revision 1.24 ed.), Dec. 2005.

[15] A. M. Jabbar, "Multi-link Iridium satellite data communication system," Master's thesis, University of Kansas, Lawrence, USA, 2001.

[16] M. Margaret., in R. Rathbarn (ed.), "Measuring Latency in Iridium Satellite Constellation Data Services," Naval Academy Annapolis, Report Number: A291464, Maryland, USA, June 2005.

[17] R. Mukaro, "A microcontroller-based data acquisition system for solar radiation and environmental monitoring," *Instrumentation and Measurement, IEEE Transactions,* vol. 48, no. 6, pp. 1232-1238, 1999.

[18] J. Terradillos, M. Bilbao, J.I. Ciria, A. Malagan, and J. Ameya "Oil Analysis as an improvement tool for the behavior of windmill gears. Main problems detected through the lubricant condition," European Lubricating Gears Institute, Prague, 2006.

[19] W. L. Winston, Operations Research, *Applications and Algorithms*, Third edition, International Thomson Publishing, Belmont, California 94002, 1994.

[20] Izrail' Solomonovich Gradshtein and Iosif Moiseevich Ryzhik, Table of Integrals, Series, and Products, Alan Jeffrey ed., San Diego, CA, USA: Academic Press, Inc., 5th ed., p. 2, 1994.

[21] MATLAB® Help files

[22] Retrieved November, 2007, http://www.defense-update.com/newscast/0207/news/160207_iridium.htm

[23] Retrieved April, 2008, http://en.wikipedia.org/wiki/Amateur_radio_frequency_allocations

[24] Retrieved April, 2008, http://electronics.howstuffworks.com/ham-radio2.htm

[25] M. Benghanem, and A. Maafi, “Data acquisition system for photovoltaic systems performance monitoring,” *Instrumentation and Measurement, IEEE Transactions,* vol. 47, no. 6, pp. 30-33, Feb. 1998.

[26] M. Gagliarducci, D. A. Lampasi, and L. Podestà, “GSM-based monitoring and control of photovoltaic power generation,” *Measurement*, vol. 40, no. 3, pp. 314-321, Apr. 2007.

[27] http://www.digi.com/technology/rfmodems/poweroutput.jsp

[28] F. Y. Khan, “Development and Analysis of a Data Transmission System for Oil Exploration Sites,” in *10th International Multitopic Conference, 2006. INMIC '06. IEEE*, (Islamabad, Pakistan), pp. 62-67, Dec. 23-24, 2006.

[29] R. J. Leopold and A. Miller, “The IRIDIUM communications system,” *IEEE Proceedings*, vol. 12, no. 2, pp. 6-9, 1993.

[30] K. Maine, C. Devieux, and P. Swan, “Overview of IRIDIUM satellite network,” in *Conference Record Microelectronics Communications Technology Producing Quality Products Mobile and Portable Power Emerging Technologies WESCON/95*, (San Francisco, CA, USA), pp. 483-490, Nov. 7-9, 1995.

[31] S. P. Munoz Aguiar, and M. J. Soteldo Perez, “Experience in OPGW Cables Selection for Overhead Transmission Live Lines,” in *TDC, IEEE Transmission and Distribution Conference and Exposition*, (Latin America), pp. 1-6, Aug. 2006.

[32] J. Campbell, *The RS-232 Solution*, SYBEX, Inc 2021 Challenger Drive #100, Alamenda, CA 94501.

[33] M. D. Seyer, *RS-232 Made Easy: Connecting Computers, Printers, Terminals, and Modems,* Prentice-Hall, Inc., Englewood Cliffs, NJ, 1984.

Appendix A

Appendix

A.1 The 9601 SBD Transceiver Pin Configuration [14]

Table A.1 gives the pin details of the 9601 SBD transceiver containing the pin numbers and its corresponding signal names, signal direction with respect to the 9601 transceiver, the function of the signal and the signal levels.

Table A.1: 9601 SBD transceiver pin configuration

Pin Number	Signal Name	Signal Direction (WRT 9601)	Signal Function	Signal Level
1	EXT_PWR	Input	Supply	+5 V +/- 0.5 V
2	EXT_PWR	Input	Supply	+5 V +/- 0.5 V
3	EXT_PWR	Input	Supply	+5 V +/- 0.5 V
4	EXT_GND		Supply return	0 V
5	EXT_GND		Supply return	0 V
6	EXT_GND		Supply return	0 V
7	ON/OFF	Input	On/Off control input	On: 2 V to supply Off: 0 V - .5 V I=120 µA max
8	Reserved			
9	Reserved			
10	SIG_GND		Signal ground	0
11	DF_S_TX	Input	Data port, serial data into 9601	RS-232
12	DF_S_RX	Output	Data port, serial data from 9601	RS-232
13	SIG_GND		Signal ground	0 V

14	DF_DCD	Output	Data port, Data Carrier Detect	RS-232
15	DF_DSR	Output	Data port, Data Set Ready	RS-232
16	DF_CTS	Output	Data port, Clear to Send	RS-232
17	DF_RI	Output	Data port, RI	RS-232
18	DF_RTS	Input	Data port, Request to Send	RS-232
19	DF_DTR	Input	Data port, Data Terminal Ready	RS-232
20	SIG_GND		Signal ground	0 V
21	Reserved			
22	Reserved			
23	SIG_GND		Signal ground	0 V
24	NETWORK_AVAILABLE	Output	Set to logic 1 when the network is visible	2.9 V CMOS
25	Spare			
26	+2V9	Output	Supply output	+2.9 V +/- 0.15 V 50 mA max

A.2 The RS-232 Connection between the 9601 Transceiver and PIC8722

The PIC8722 board has two RS-232 3-wire connection ports. For communication between the PIC8722 (a Data Communication Equipment (DCE)) and the 9601 SBD transceiver, also being a DCE, a 3-wire custom made crossover cable was made and used. The parameters set for the two RS-232 ports [32][33] of the PIC8722 and the PC port for monitoring is given in Table A.2.

Table A.2: Parameter values for RS-232 ports

Parameters	PC COM port	PIC8722 Port1	PIC8722 Port2
Bits/sec	19200	19200	19200
Data bits	8	8	8
Parity	None	None	None
Stop bit	1	1	1
Flow control	Hardware		

Also, as the 9601 is by default in a 9-wire mode, it was converted to a 3-wire configuration with specific ATCs (AT&D0 and AT&K0) via the hyper-terminal program of Windows xp. The RS-232 connection between the PIC8722 and the PC, which is basically for monitoring, was done with a straight through DB9 cable.

A3. The Power Tray Features and Specifications

The Iridium 9601 SBD DB9 power tray is used as a power platform for the 9601 transceiver. It has a barrel connector for power connection, a DB9 RS-232 serial interface, an enable/disable switch and two status LEDs. The on-board Switch Mode Power Supply (SMPS) on the power tray has an input voltage range from 6 Volts to 30 Volts. The red LED indicates that the power is available from the power tray. The green LED has the following meanings:

OFF: The SBD terminal is powered off. This can be controlled by the enable/disable switch in the power tray.

FLASHING: The SBD terminal is on but the satellite network is not available.

ON: The SBD terminal is on and the satellite network is available.

The DB9 serial interface has all the flow control and handshaking wires connected directly to the SBD 9601 transceiver. Hence, the 9601 transceiver connects directly to a PC with a straight-through (standard) DB9 serial cable. This connection was used initially for interfacing the transceiver with a PC and testing the 9601 transceiver.

The connection of the 12 of the 26 pins of the 9601 SBD transceiver (as described in Appendix A.1) connected to the DB9 connection of the power tray is given below:

Table A.3: Pin connection between 9601 SBD transceiver and the power tray

9601 transceiver pins	DB9 connection	Description
14	1	Data Carrier Detect
12	2	Data from 9601
11	3	Data into 9601
19	4	Data Terminal Ready
10, 13, 20, 23	5	Signal Ground
15	6	Data Set Ready
18	7	Request to Send
16	8	Clear to Send
17	9	RI

Appendix B

Appendix

B.1 Field Application Design Code in the CCS C

```
*******************************************************************
// This program implements the MO message transmission from the FA and MT message
reception at the FA at set intervals.
// Author: Ujjwal Deep Dahal
// Created on: April 30, 2008
*******************************************************************

#include <18f8722.h>
#device ICD=TRUE
#fuses HS,NOLVP,NOPROTECT,NOWDT
#use delay (clock=20000000)

// RS-232 ports initializations.  Two RS-232 ports of PIC8722 are used for the purpose of
// connecting the PIC8722 to the 9601 transceiver and for monitoring the communication
// between them with a PC during testing.
#use rs232 (baud=19200, bits=8, parity=N, stop=1, xmit=PIN_C6, rcv=PIN_C7,
ERRORS, stream=PORT1)
```

```
#use rs232 (baud=19200, bits=8, parity=N, stop=1, xmit=PIN_G1, rcv=PIN_G2,
ERRORS, stream=PORT2)

// ‘Writing the string AT, AT+SBDWT and AT+SBDI’ function declaration
void WriteString1(char*);

// ‘Reading the response of AT and SBDWT’ - function declaration
char ReadString1(char*);

// ‘Reading the response of SBDI’- function declaration
char ReadString2(char*);

//'Reading the MT message' - function declaration
char ReadString3(char*);

// ‘Writing the strings AT, AT+SBDWT and AT+SBDI’- function definition
void WriteString1(char* val) {
  while (*val != 0x00) {
    fputc(*val, PORT2);
    val++;
  }
}
```

```
// 'Reading the response of AT and AT+SBDWT' - function definition
  char ReadString1(char* val) {
  char* temp;
  int a=0;
  temp = val;

   do {
     *val = fgetc(PORT2);
     if(*val= =0x0A)
     a++;
     val++;
     }while (a!=2);

  do {
     fputc(*temp, PORT1);
     if(*temp==0x0A)
     a++;
     temp++;
  }while (a!=4);
 return *val;
}
```

```
// 'Reading the response of AT+SBDI' function definition
 char ReadString2(char* val) {
  char* temp;
  int a=0;
  temp = val;

 do {
    *val = fgetc(PORT2);
    if(*val==0x0A)
    a++;
    val++;
    }while (a!=4);

do {
    fputc(*temp, PORT1);
    if(*temp==0x0A)
    a++;
    temp++;
  }while (a!=8);
 return *val;
}
```

```
// Variable declaration
// K counts the number of times the overflow_counter overflows to keep track of the
// elapsed time.  The counter overflows ever 3.27 ms.  Hence, depending on the timing
// requirements of the modules to be executed at a certain time, the corresponding values
// of K can be calculated and when it overflows K times the required interrupt can be
// invoked.
int32 overflow_counter = 0;
int32 K=1305;
int data_session_time=0;

// Interrupt routine which gets invoked on every overflow
#int_timer1
void timer1_isr(){
if (overflow_counter<K){
overflow_counter++;
data_session_time=0;
}
else{
data_session_time=1;
overflow_counter=0;
}
}
```

```
// The main program starts here
void main() {
   char initString1[] = {'A', 'T', 0x0D, 0x00};
   char initString2[] ={'A', 'T', '+','S', 'B', 'D', 'W','T', '=',0x00};
   char initstring3[] = {'A', 'T', '+', 'S', 'B', 'D', 'I', 0x0D, 0x00};
   char initstring4[] = {'A', 'T', '+', 'S', 'B', 'D', 'D', '0' 0x0D, 0x00};
   char initstring5[] = {'A', 'T', '+', 'S', 'B', 'D', 'R', 'B' 0x0D, 0x00};
   char response1[205];
   char response2[205];
   char response3[205];
   char MT[100];
   char sbd[205]={0x68,0x65,0x6c,0x6c,0x6f,0x0D,0x00};

    setup_timer_1(T1_INTERNAL|T1_DIV_BY_1);
    set_timer1(0);
    enable_interrupts (int_timer1);
    enable_interrupts (global);

    while(TRUE){
      if (data_session_time){
```

```
//'Writing the string (AT) and AT+SBDWT' function call
    HH: WriteString1(initString1);

//'Reading the response of AT' function call
    ReadString1(response1);
    if(response1[5]!=0x4F)
    goto HH;
    putc(response1[5], PORT1);

// ‘Writing the string AT and (AT+SBDWT)’ - function call
    II: WriteString1(initstring2);
    WriteString1(sbd);

// ‘Reading the response of AT+SBDWT’ - function call
    ReadString1(response2);
    putc(response2[15], PORT1);

// ‘Writing the string AT+SBDI’ - function call
    JJ: WriteString1(initstring3);

// ‘Reading the response of AT+SBDI’ - function call
    ReadString2(response3);
    if(response3[17]= =0x32)
```

```
      goto HH;

      putc(response3[17], PORT1);


      // 'MT Message Reading' - function calls


      WriteString1(initstring4);

      ReadString2(response1);

      WriteString1(initstring3);

      ReadString2(response2);

      WriteString1(initstring5);


// Calling the MT massage read function,("ReadString3")

      ReadString1(MT);

     }                          // End of TRUE of data_session_time

       else {

 fputc (0x41,PORT1);  // Basically do nothing, here writing 'A' for display during

                            // testing

       }                     // End of FALSE of data_session_time

   }                         //End of while loop

}                            // End of main program
```

B.2 System Implemented

Figure B.1 gives the picture of the system implemented, showing the 9601 transceiver [30] connected to the PIC microcontroller with DB9 RS-232 cable in the 3-wire mode. It also shows the cables, lightning arrestor and the antenna. The PC is used here for the purpose of monitoring the testing of the system.

Figure B.1: Picture of the system implemented

B.3 Additional Test Results and Explanations

Figure B.2 is a compilation of the responses of the 9601 transceiver when it was trying to initiate a satellite session with an ATC (AT+SBDI) for an MO message transmission from the field. It was seen that even though the green LED was in the ON state, meaning that the network was available, the MO message transmission failed, three times consecutively, which is given by the digit “2” of the response “+SBDI: 2, 9, 2, 0, 0, 0” in the first three quadrants of the figure below. This is read via one of the two RS-232 ports of the PIC8722, connected to the PC, with a serial port monitor. The program in the PIC8722 continuously tries to initiate the satellite session until it is successful. Hence, is seen that at the fourth trial the first digit of the response is a value “1”, as seen in the fourth quadrant, indicating that the MO SBD message was successfully sent from the ISU to the ESS.

AT+SBDWT=hello OK AT+SBDI +SBDI: 2, 9, 2, 0, 0, 0	AT+SBDWT=hello OK AT+SBDI +SBDI: 2, 9, 2, 0, 0, 0
AT+SBDWT=hello OK AT+SBDI +SBDI: 2, 9, 2, 0, 0, 0	AT+SBDWT=hello OK AT+SBDI +SBDI: 1, 9, 1, 4, 9, 0

Figure B.2: Test result for Mobile Originated message transmission

Appendix C

Appendix

C.1 MATLAB® Code for Exhaustive Search Algorithm to Solve the Non Linear Programming

```
*********************************************************************
% This program implements the exhaustive search algorithm to solve the NLP and
% also plots the sample solution of Npg, Nmi and Nei and its corresponding R.
% objective functions
% Author: Ujjwal Deep Dahal
% Created on: May 30, 2008
*********************************************************************
% Exhaustive Search Algorithm
clear all; clc; close all;


% Objective Function coefficients
r = [50 30 10];
table0 = [0 0 0 0];


%Coefficients of Data byte constraint
c1 = [1 1 1];
c11 = 41;
```

```
%Coefficients of PME constraint
c2 = -[1/40 -1 1/16 -1/2 -1 1/80 410];
c21 = 0;

% The exhaustive search algorithm
for Npg = 1 : 41 ,
   for Nmi = 1 : 41 ,
      for Nei = 1 : 41,
         N1  =  [ Npg Nmi Nei ].' ;
         N2  =  [ Npg^2 Npg Nei^2 Nei Nmi Npg*Nei 1].' ;
         if ((c1*N1<=c11) && (c2*N2<=c21))
            R = r*N1 ;
            table0   =   [  table0  ;  [ Npg Nmi Nei R ]  ] ;
          end
      end
   end
end
```

% Extracting the samples of N_{pg}, N_{mi} and N_{ei} from the solution points, for plotting

```
t1=table0(1:10,1:3);
t2=table0(2000:2010,1:3);
t3=table0(5000:5010,1:3);
t4=table0(7000:7010,1:3);
```

```
t5=table0(9000:9010,1:3);

t6=table0(10651:10661,1:3);

all=[t1;t2;t3;t4;t5;t6];


%Extracting the corresponding samples of R, from the solution points, for plotting

o1=table0(1:10,4);

o2=table0(2000:2010,4);

o3=table0(5000:5010,4);

o4=table0(7000:7010,4);

o5=table0(9000:9010,4);

o6=table0(10651:10661,4);

oall=[o1;o2;o3;o4;o5;o6];


%Plotting Npg, Nmi and Nei and its corresponding R values

figure(1);

p=1:65;

bar (all,'stack')

xlabel ('Sampled Solution Points (Numbers)')

ylabel ('Sub-Frame (Numbers)')

h1 = gca;

h2 = axes('Position',get(h1,'Position'));

plot (p,oall,'k','LineWidth',3)

set (h2,'YAxisLocation','right','Color','none','XTickLabel',[])
```

```
set (h2,'XLim',get(h1,'XLim'),'Layer','top')

pause

% The function to plot the constraints
hold off ;

% Plotting the Data byte size constraint
x1  =  [ 0 41  0  0 0  0 41 0  0 ] ;
y1  =  [ 0  0 41  0 0  0  0 0 41 ] ;
z1  =  [ 0  0  0 41 0 41  0 0  0 ] ;
figure(2);
plot3(x1,y1,z1,'ok-.') ;
hold on
view([145,45]) ;
grid ;

% Plotting the PME constraint
for Nei = 1:41:41;
for Npg = 1:41;
Nmi(Npg,1) = 10/(20^2)*(Npg -(80 - Nei)/4)^2 +10;
end
Npg = 1:41;
```

```
Nei = 1:41;
plot3 (Npg,Nei,Nmi,'k')
xlabel ('PD Sub-frames(Npg)')
ylabel ('ED Sub-frames(Nei)')
zlabel ('MD Sub-frames(Nmi)')
end
```

C2. MATLAB® Code for Non Linear Programming Solution with Built-in Functions

```
*********************************************************************
% This program is for solving the NLP with the built-in functions in MATLAB®
% Author: Ujjwal Deep Dahal
% Created on: May 15, 2008
*********************************************************************

% Step 1: Writing an M-file for the objective function
function f = objfun(x)

% The negative sign for the objective function is given to get the maximization of the
% objective function as function 'fmincon' gives the minimum value in return

f = -1*(50*x(1)+30*x(2)+10*x(3));
```

% Step 2: Writing an M-file for the constraints

```
function [c, ceq] = confun(x)
c = [x(1)+x(2)+x(3)-41; -x(1)+1; -x(2)+1; -x(3)+1; (-x(1)^2]/40+ \\
    x(1)-(x(3)/16)^2+((x(3)*x(2))/2)-((x(1)*x(3))/80)-410];
ceq = [];
```

%Step 3: Invoking the constrained optimization routine

```
clear all;
close all;
clc;
```

% Randomly guessing the decision values

```
x0 = [1; 1; 1];
lb = [0;0;0];
options = optimset('LargeScale', 'off');
[x,fval] = fmincon(@objfun, x0, [],[],[],[],lb,[],'confun',options)
```

Curriculum Vitae

Candidate's full name: Ujjwal Deep Dahal

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Work experience: Worked in Bhutan Power Corporation Ltd. from 2002-2006.

Publications:

U. D. Dahal, B. R. Petersen, and J. Meng, "Iridium Communication System for Data Telemetry of Renewable Distributed Generation System," in *24th Biennial Symposium on Communications,* (Kingston, Ontario, Canada), pp. 262-265, June 24-26, 2008.