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Data Compression for Smart Grid Infrastructure

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Data Compression for Smart Grid Infrastructure

Abstract

Embedded systems, which work with large data sets, need larger memory and consume much more data traffic when compared to other IOT (Interne Of Things) devices. In this study, Huffman's Lossless Compression Algorithm is optimized and implemented on a *Electric Meter Reader Modem (DR-502-DCL)*. Compression Algorithm used for storing the data which is measured by the electric meter. Huffman's Algorithm optimized for memory (RAM) on a multi-threaded embedded system. STM32F412 microcontroller and Winbond 128mbit embedded flash memory is used for this study. Compression ratio of %59 is reached with eliminating repetitive character groups.

Keywords: Huffman, Embedded, Lossless, Compression, Memory Optimized

Akıllı Elektrik Şebekeleri için Veri Sıkıştırma

Özet

Büyük veri gruplaryla çalışan gömülü sistemler diğer IOT (Internet of Things) cihazlarına kıyasla daha fazla hafıza ve internet trafiği kullanırlar. Bu çalışmada Huffman'ın kayıpsız sıkıştırma algoritması DR-502-DCL model elektrik sayacı okuyucu modemine uygulanmıştır. Sıkıştırma algoritması, sayaç verilerinin depolanması için kullanılmıştır. Huffman'ın sıkıştırma algoritması RAM kullanımı ve multi-thread işletim sistemi için optimize edilmiştir. STM32F412 mikrokontrolör ve Winbond marka 128mbit'lik entegre flash bellek kullanılmıştır. Bu çalışmayla %59'luk bir sıkıştırma oranı elde edilmiştir.

Anahtar kelimeler: gömülü sistem, Huffman, kayıpsız sıkıştırma, hafıza optimizasyonu

Acknowledgements

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To my family and friends…

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List of Abbreviations

AMI	**A**dvance **M**etering **I**nfrastructure
AMR	**A**utomated **M**eter **R**eading
EDC	**E**lectric **D**istribution **C**ompany
GPRS	**G**eneral **P**ackage **R**adio **S**ervice
GSM	**G**lobal **S**ystem for **M**obile communication
IOT	**I**nternet **o**f **T**hings
KB	**K**ilo**b**yte
Kb	**K**ilo**b**it
MCU	**M**icro **C**ontroller **U**nit
NB	**N**arrow **B**and
PLL	**P**hase-**L**ocked **L**oop
PM	**P**rogram **M**emory
RAM	**R**andom **A**ccess **M**emory
ROM	**R**ead **O**nly **M**emory
RSSI	**R**eceived **S**ignal **S**trength **I**ndicator
RTOS	**R**eal **T**ime **O**perating **S**ystem
SMPS	**S**witch **M**ode **P**ower **S**upply
SPI	**S**erial **P**eripheral **I**nterface
TCP	**T**ransmission **C**ontrol **P**rotocol
UART	**U**niversal **A**synchronous **R**eceive **T**ransmit
USART	**U**niversal **S**erial **A**synchronous **R**eceive **T**ransmit

Chapter 1

Introduction

1.1 Interconnected Electric Grid Network

Electric distribution system is one of the biggest engineering project that affects billions of people. Key problem is, electric generating power stations are not always located near urban places. So that, generated power must be delivered long distances, this can as long as a continental. Long distance transmission voltages can be as high as 275kV. Energy and electric distribution companies manage this electric grid network. These companies also manage billing processes of their customers. On large scale Automated Meter Reading (AMR) system significantly reduce companies operating costs. Also, technical and non-technical losses can be measured with this network. In addition to billing and losses, this AMR/AMI (1.2) system provides analytic data to power companies' databases for forecasting consumptions. Estimating future consumption trends, helps these firms to maintain the integrity of interconnected power grid network.

1.2 Advanced Metering Infrastructure

AMI (Advanced Metering Infrastructure) is a data measurement and collection architecture, which uses smart meters, communication networks, and data management systems. In Turkey, electric theft and price competition forces companies to cut leaks and optimize power generation. Electric Distribution Companies

(EDC) collect valuable data with AMI. Basically a simple "Electric Meter Reader" collects consumption data and transfers it to EDC's head-end servers.

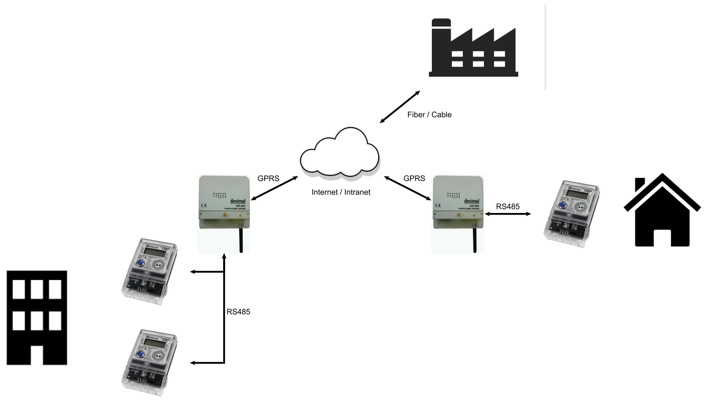


Figure 1.1: AMI Data Flow

In Figure 1.1 electric meter data flow is shown. Meter Readers collect consumption analysis from electric meters over an RS485 serial communication channel. Meter Readers transfer the collected data to Power Companies' Servers over internet/intranet using GSM/GPRS network infrastructure. Power-line and RF applications are used for communication, however these methods are not feasible for most applications due to bandwidth and range limitations. Eliminating bandwidth factor, compression is crucial on AMI/AMR applications.

Collected data used to billing and estimating future loads on electric grid. As a course of its nature, excess production of electric power will be lost on the electric grid. To reduce costs and increase efficiency, EDC's estimate future load statistics on the electric grid. Currently 600.000 electric meters are connected to internet in Turkey. Every year, minimum 150.000 new electric meters connecting to the internet in Turkey. This increase will also add an extra load on communication networks. Today, 2G GSM network in some of the villages in Turkey have reached their maximum capacity which caused by electric meter readers. For this reason EDC's testing different type of communication networks such as Powerline, RF, and NB-IOT communications.

For example, RF (Radio Frequency) Communication is one of the most popular method for IOT. It is cheap to produce, cheap to operate, can be easily found on the market. On the other hand, it has a major limitation of very low data bandwidth when it is optimized for usable distances on AMI applications. Data statistics, which is needed by EDC's, are extremely huge for RF communication. When compared with GSM network, RF communication can be less redundant then GSM infrastructure. Also in some areas, communication and power network can be unstable. Collected data can not be transferred for one or two months. For this reason, Electric Meter Readers need fairly larger flash memory to store collected data.

The key point is compression of the data produced by the smart meters and reduce the size of it in the network and device. Data Compression is some kind of signal processing technique which encodes information using fewer bits and reduces file size. In general, data compression technique divides into two groups which are *Lossless Compression* and *Lossy Compression*. Lossy compression ratio is much better than lossless compression ratio. However, some of the information is lost during the compression process. On this application *Lossy Compression* is not an option.

In this report, some of the parts of the development will not be detailed due to copyright.

1.3 Compression on AMI/AMR

Advance Metering Infrastructure uses many Data Concentrator Units *(DCU)* to collect data. Production cost of the DCU's extremely important to make AMI/AMR system feasible. Therefore, DCU's resources are limited. In this study, STM32F4 model microcontroller (Appendix F) used for programming. The MCU has 256KBs of ram, and conventional compression algorithms need much larger memory space to compress data. On embedded system, these compression libraries allocate RAM as much as the data which will be compressed. In the end of the compression process allocated RAM space is released. However, this allocation and release cycle makes RAM space fragmented. After a couple of compression process, fairly larger memory allocations can not be done by the program. This strategy called *Dynamic Heap Memory* and makes the program less determinant. Work-around of fragmented RAM is using *Static Heap Memory* strategy. In this strategy all memory allocations done in the beginning of the execution.

Chapter 2

Literature Survey

2.1 What is data compression?

Data compression, also known as source coding [1] or bit-rate reduction, is representing [2] data using fewer bits. Basically, compression methods divide into two, which can be either lossy or lossless. Lossless compression reduces bits by identifying and eliminating statistical redundancy. No information lost in compression process. However, lossy compression reduces bits by removing unnecessary or less important information [3]. The process of decreasing file size of the data is often referred to as data compression. In data transmission, it is called source coding because the data is encoded before transmission (or storing) at the source side of the channel [4]. Compression is very useful when the systems resources are limited. In IOT world memory sizes and data transmission bandwidth are very low and managing these resources play an important role. On the other hand, computational resources are consumed in the process of compression. However decompression need lesser resources. Data compression is subject to a spacetime complexity trade-off. For example, a compression scheme for video may require huge amount of computational load on a special hardware. On the other side, decompression process can be done on a generic CPU fast enough to play the video in real time. The design of data compression schemes involves trade-offs between various factors such as degree of compression, the amount of distortion (when using lossy data compression), memory and CPU usage [5] [6].

2.2 Lossless Compression

Lossless data compression algorithms usually exploit statistical redundancy [7] to represent data without losing any information, so that the process is reversible. Lossless compression is practical enough to use because most real-word data have statistical redundancy. For instance, consecutive frames of a video file have minor pixel changes between them. Some of the information can be reused to represent the next frame.

2.3 Arithmetic Coding

Arithmetic coding is a form of entropy coding used in lossless data compression. For example, a string of characters such as Hello World is represented using a fixed numbers for each character as in the ASCII code. When a string is compressed with arithmetic coding, frequent characters represented with fewer bits and less frequent ones uses longer bit sequences. However, arithmetic coding differs from other forms of entropy coding such as Huffman Coding, in that rather than assigning each symbol to a more efficient bit sequence, arithmetic coding encodes entire message into a single number, an arbitrary-precision fraction q where between 0 and 1 [8].

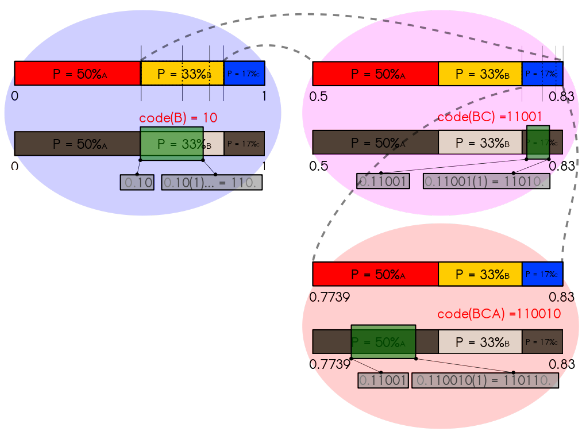


Figure 2.1: Arithmetic Coding Example

In Figure 2.1, an arithmetic coding example assuming a fixed probability distribution of three Symbols “A”, “B”, and “C”. Probability of “A” is 50%, probability of “B” is 33% and probability of “C” is 17%. Furthermore, we assume that the recursion depth is known in each step. In step one we code “B” which is between the interval [0.5, 0.83). The binary number “0.10x” is the shortest code that represents an Interval that is entirely inside [0.5, 0.83). “x” means an arbitrary bit sequence. There are two extreme cases: the smallest x stands for zero which represents the left side of the represented interval. Then the left side of the interval is dec(0.10) = 0.5. At the other extreme, x stands for a finite sequence of ones which has the upper limit dec(0.11) = 0.75 Therefore, “0.10x” represents the interval [0.5, 0.75) which is inside [0.5, 0.83) Now we can leave out the “0.” part since all intervals begin with “0.” and we can ignore the “x” part because no matter what bit-sequence it represents, we will stay inside [0.5, 0.75).

2.4 Huffman Coding

Huffman Coding [9] is an entropy coding algorithm. It is used for lossless data compression in computer science and information theory. Huffman Code is a variation of *prefix code* which is commonly used for variable-length coding. The output of Huffman's algorithm generates a variable-length code table for encoding a source symbol. The algorithm generates this table by looking at the estimated or calculated probability or frequency of occurrence for each possible value of source symbols. Most frequent characters get smaller codewords and less frequents get longer codewords.

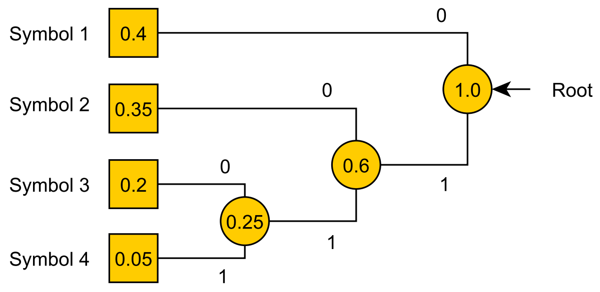


Figure 2.2: Example Graph

For instance; there is a source generating 4 different symbols $\{s_1, s_2, s_3, s_4\}$ with frequency $\{8; 7; 4; 1\}$ and probabilities are $\{P_{s_1} = 0.4, P_{s_2} = 0.35, P_{s_3} = 0.2, P_{s_4} = 0.05, \}$. Generate a binary tree from left to right taking two less probable symbols and connect them together and sum their probabilities. Introduce the new node as a new symbol and continue to find next less probable two symbols and connect them until there is one symbol left.

Symbol	Codeword
s_1	0
s_2	10
s_3	110
s_4	111

Table 2.1: Example Codeword Table

This method works by creating a binary tree. Every symbol in the code represented as a leaf node and there are $SymbolCount - 1$ internal nodes occurs in this binary tree.

2.5 Lossy Compression

In this method some loss of information is acceptable. Eliminating nonessential information from the data source can save storage space. Lossy data compression algorithms (or filters) designed by research on how humans perceive the data in question. For instance, human eye is more sensitive for variations in luminance then in color. JPEG compression trims off nonessential bits of information. [10]. Besides, there is a trade-off between preserving information and reducing size of the data file.

Nearly all of the digital cameras are using image compression to increase storage capacities with minimal degradation of picture quality. Similarly, DVDs use lossy data compression MPEG-2 and Blu-Ray Discs are using H264 compression formats for video compression.

In lossy audio compression methods, non-audible or less audible components of audio signal is removed from the source to reduce the file size. This removal process defines compression ratio. However, audiophiles say that removed components always reduce the quality of music significantly.

Chapter 3

Requirements

Before starting the design and development process, *Dicle Electric Distribution Company's (DEDAS)Modem Purchase Auctions's* requirements must be followed (Appendix E). Some of the key points of the requirements are listed below.

1. Modem must hold 16 electric meters' data for at least 2 months.
2. Voltage rating is 220VAC 50Hz.
3. Modem must be immune to electromagnetic noise (EMC [11], LVD [12]).
4. Supports meter communication protocol IEC62056-21 [13] Mod A/B/C DLMS/COSEM [14].
5. 2 RS485 Serial communication ports
6. 1 GSM Module
7. Status indicators for Power, GSM, RSSI, and Serial Port activity.

In Turkey, every commercial electronic device must comply with EMC [11] and LVD [12]. Most of the electric meters used in Turkey communicates with IEC62056-21 [13] protocol, therefore the designed device must be compatible with it. Also device needs an RS485 serial communication port to connect with electric meters. The most important requirement for this study is the first one, which affects devices memory capacity. In worst case scenario, device must capable to store 23MBs (Eq. 3.1) of RAW meter data on its memory. Worst case, an electric meter will produce 23KB per day (Table 5.1).

$$\begin{aligned} SingleEM &= 23(KB/Day) \times 60(Days) \approx 1.4(Megabytes/TwoMonths) \\ Total &= 1.4(Megabytes) \times 16 = 22.4(Megabytes) \end{aligned} \tag{3.1}$$

Chapter 4

Electronic Circuit Design

Before starting the design, a draft sketch is done with respect to basic requirements (Chapter 3).

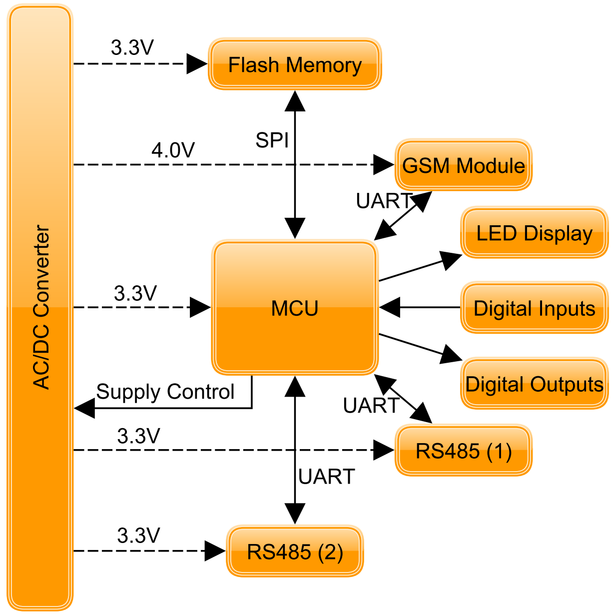


Figure 4.1: Schematic Sketch

In Figure 4.1, as a power stage an AC/DC converter circuit is used to supply current to the components. Each required voltage can be seen. There is an MCU in the middle of the sketch which basically controls every other component. In this study various communication protocols are used, such as communication between flash memory and MCU is a Serial Peripheral Interface *(SPI)*. Also, GSM Module is communicating with an Universal Asynchronous Receiver Transmitter *UART* protocol. In addition to USART communication with GSM module, also two RS485 level converters are connected to the MCU with USART. After this sketch design, listed steps are as follows:

1. Components Selection
2. Schematic Design
3. Design

4.1 Component Selection

Component selection is one of the key points in the design. In this thesis, Micro-controller and Flash Memory are the most important ones. Each components must be found easily on the market, have a decent technical support, price/performance ratio must be good, and must match the minimum requirements.

4.1.1 Micro-controller

Micro-controller is communicating with 2 serial level converters, GSM module, and External Flash Memory. GSM module of the circuit is using an UART serial communication port and Flash memory is using SPI. When software development process is taken into account, MCU needs at least 120KB of RAM. For this specifications we choose ST Microelectronics STM32F412RET model MCU (Appendix F).

- 256KB RAM
- 6 UART/SPI
- 64 GPIO

- 512KB PM
- 6 Timers
- Watchdog Timer
- Real Time Clock (Internal and External Clock Source)
- 8Mhz of internal RC Clock (External Clock Optional)
- 96Mhz of Main Clock Speed with PLL.

4.1.2 External Flash Memory

Winbond W25Q256FV model Flash memory, which has 32 Megabytes of memory, is enough. However, with compression algorithm 30 Megabytes of RAW Meter data is compressed to 15 Megabytes. Therefore, 16 Megabyte version is more suitable, and W25Q128FV model flash memory is selected.

4.2 PCB Design

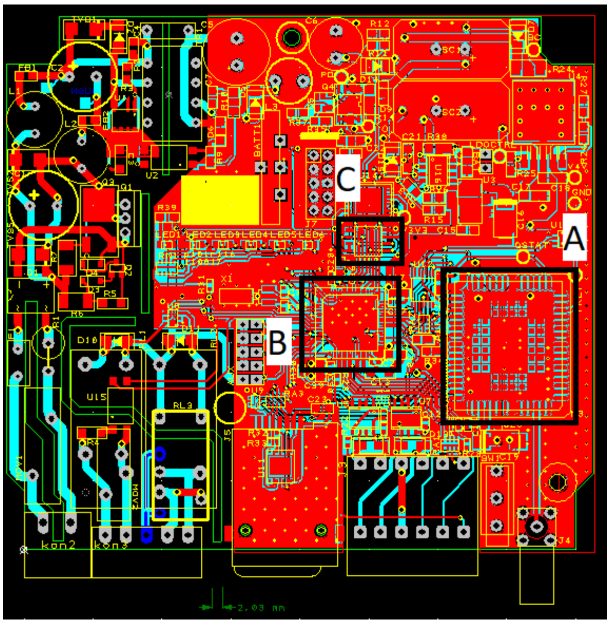


Figure 4.2: Final Gerber Design, A: GSM Module, B: Microcontroller, C: Flash Memory

When designing the PCB, components reference designs considered. In Figure 4.2, SMPS part is placed on the left hand side. MCU positioned in the middle bottom of the circuit board to keep communication connections shorter for eliminating GSM signal interference. Final form of the PCB is shown in Figure 4.3.

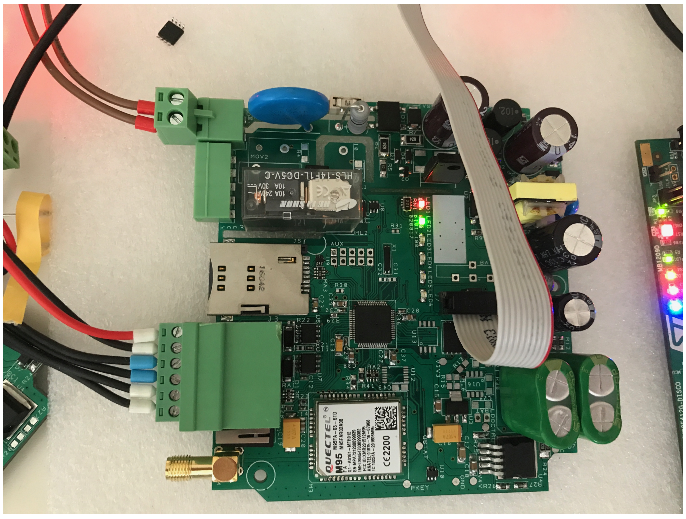


Figure 4.3: Final PCB

Chapter 5

Software Development

Software development constitutes nearly %70 of the general development progress. In this section Software architecture and Huffman Compression Algorithm's implementation is explained.

5.1 Pre-Analysis

Meter Brand	Meter Model	Read Out Size	Load Profile Size	Total (per day)
Köhler	AEL.TF 20	11KB	4KB	15KB/Day
Köhler	AEL.TF.21	17KB	6KB	23KB/Day
Luna	LUN4/5	2KB	7KB	9KB/Day
Makel	MSY.C410	7KB	4KB	11KB/Day
Makel	MSYC500	7KB	1KB	8KB/Day
Viko	VEMC	10KB	2KB	12KB/Day

Table 5.1: Meter Models Data Sizes

In Table 5.1, most common used electricity meters in Turkey is listed. When Meters' daily RAW data sizes are compared, AEL.TF.21 produces biggest data. Previous calculations shows that nearly 30 Megabytes of meter data must be compressed into 15 Megabytes. Thus, minimum compression ratio:

$$CompressionRatio = \frac{30(MB)}{15(MB)} = 2:1 \tag{5.1}$$

In worst case scenario, every character of the ASCII table is used. With respect to that, mapping table has 128 lines. Each line has 3 columns of 16 bit integers.

$$HeaderSize = (128Lines \times 3Columns \times 2Bytes) + (3 \times 4Bytes) = 780Bytes \tag{5.2}$$

If two sectors of the external flash memory are used to hold the data, that leaves 8 Kilobytes of memory space. In worst case scenario, actual useable space equals to:

$$UsableSpace = 8(Kilobytes) - 780(Bytes) = 7412(Bytes) \tag{5.3}$$

Calculate for minimum compression ratio for AEL.TF.21's Read Out data(17KB);

$$CompressionRatio = \frac{17408(Bytes) - 7412(Bytes)}{17408(Bytes)} x100 = \%57.42 \tag{5.4}$$

Compression performance is close to entropy when Huffman Coding is used. Calculated entropy values are shown below(Table 5.2).

$$H(X) = \sum_{i=1}^{M} p_i \log_2(\frac{1}{p_i}) \tag{5.5}$$

Meter Brand	Meter Model	Entropy Read Out	Uniqe Sym. Read Out	Entropy Load PRFL	Uniqe Sym. Load PRFL
Kohler	AEL.TF.20	4.1500	51	3.7952	31
Kohler	AEL.TF.21	4.1271	51	N/A	N/A
Luna	LUN4/5	4.2509	35	4.0217	31
Makel	MSY.C410	4.0787	37	2.3558	23
Makel	MSYC500	4.0379	37	3.9779	28
Viko	VEMC	4.1403	40	3.7039	26

Table 5.2: Entropy and Unique Symbols

In Table 5.2, each electricity meters' unique symbol counts and their measurement data's entropy calculations can be compared. Nearly all of the electricity meters never use full ASCII table.

5.2 Software Architecture

Different than other embedded systems, an operating system (Free RTOS [15]) is used for organizing internal processes. In this architecture, four threads are used in the design.

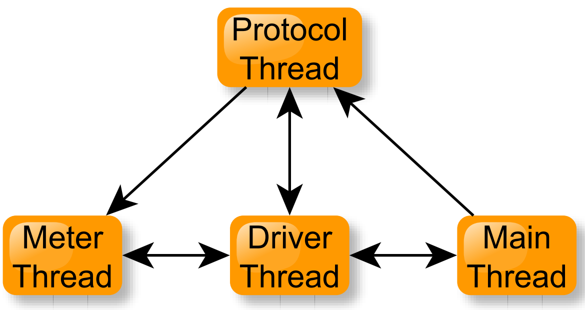


Figure 5.1: Thread Hierarchy

In Figure 5.1 interactions of threads, which are used in this study, are shown. Protocol thread controls hardware drivers and manages meter reading sequences.

Also main thread has access to hardware drivers and protocol thread to complete diagnostic tasks. More detailed explanation is listed below.

1. Meter Thread: Reads an electric meter and copies data to an external queue. Receives a job from an external queue.
2. Protocol Thread: Decodes messages packages, which comes from an remote server over TCP, and controls other threads.
3. Driver Thread: Manages MCU Peripherals and external devices as GSM, Flash Memory, Voltage Regulators etc.
4. Main Thread: This thread used for diagnostics. Overrides Protocol Thread.

5.2.1 Meter Thread

Receives a meter job from receive queue and initiates a meter reading process. Communication with electric meter completes over RS485 Port. Kohler TF 21 model Electric Meter's complete data reaches nearly 17KB. This data is compressed with *Huffman Compression Algorithm [9]* and copied to return queue.

5.2.2 Protocol Thread

Communicates with a remote server via Driver Thread. Initiates meter reading jobs, software updates, and output events. Also reports input events like case opened/closed.

5.2.3 Driver Thread

Executes GSM Module's state machine, reports input events to Protocol Thread.

5.2.4 Main Thread

This thread mainly used for diagnostic processes. Writing a configuration file, hardware testing, firmware updates, and heap analyzing processes are done by Main Thread.

5.3 Huffman Compression Algorithm

Huffman coding is a lossless data compression algorithm. Main strategy of Huffman Coding is to assign shorter keywords to most frequent characters. Besides, less frequent characters will be assigned to longer keywords. This algorithm is a type of *Variable Length Coding*.

5.4 Implementation

Micro-Controllers on embedded systems have very small and limited size of memory. In this study, RAM usage optimization is crucial. Each new allocation in Run-Time will use Heap Memory Space when RTOS is used. To eliminate stack overflow, remaining RAM space is shared with each task. Run-Time allocations slowly create fragments on heap space. At some point larger memory allocations cannot be completed due to the fragmentation. To prevent run-time memory allocation, every compression and decompression process done one at a time using a predefined memory region. As mentioned before, maximum decompressed data size can be 23KBs and compressed data size can be 8KBs per reading. Therefore, 31KBs of RAM space is pre-allocated.

5.4.1 RAM Access

In ANSI C, the smallest addressable unit is a byte. However, Huffman's codewords' length starts from 1 bit and more. These codewords appended to one another (in proper order) to get compressed data. To achieve bit level access 2 subroutine functions added to library.

WriteMemory(startByteAddress,bitAddress,value)

ReadMemory(startByteAddress,bitAddress)

5.4.2 External Flash Memory Access

Winbond flash memory uses 32bit addressing and each byte can be read directly. Initial state of each bit is *true* (logic 1). Programming means flipping the bit to *false* (logic 0) state. Whole address map of the flash divided into sectors, which is 4KB long, and erase process can be done sector by sector. Because of that file sizes look bigger on flash memories. Also each bit can be programmed nearly 100 thousand times, after that memory reaches its end of life and programming cannot be guaranteed.

Figure 5.2: File Structure

In Figure 5.2 general structure of compressed files is shown. Beginning of the file contains a header information (Figure 5.3) which contains files sizes and character mappings. Each compressed file has a CRC value at the end of the file for redundancy check. This CRC value calculated before the compression. After decompression process, CRC value is calculated and compared with the recorded value. If this two values match, file is not corrupted and can be processed.

5.4.3 Header Syntax

Figure 5.3: Header Structure

In Figure 5.3 structure of header is shown. First data represents how many unique characters are used. With this information size of the header file can be estimated. After unique character count, decompressed and compressed data lengths take place in the header part. With respect to this information compressed file size check can be done and decompression process is terminated when it is done. Final data is *Codeword Table*, each compressed data uses different codewords. This codeword table must be stored with the data for further decompression process.

- ASCII Size
- Decompressed Length
- Compressed Length
- Codeword Table

index	Orj. Code	Compressed Code	Ignored
000	'0'	1000000000000000_2	14_{10}
001	'.'	0010000000000000_2	13_{10}
002	'8'	0000000000000000_2	12_{10}
...	...	...	...
050	'Y'	0110111111101100_2	02_{10}

Table 5.3: Codeword Table

In Table 5.3, an example of character mapping table shown. Each row decodes or encodes a unique character in source code. First column of table is original

ASCII representation. Second column is generated Huffman Codes, for speeding up implementation time each Huffman code is casted into a 16 bit and left aligned. "Ignored" column defines how many bits are ignored from right of the "Compressed Code" (Huffman Code). In addition to all, table is sorted most frequent to least frequent to speed up decompression process.

5.4.4 Implementation

There are three main steps for compression.

- Frequency Analysis
- Codeword Generation
- Encoding

Frequency analysis and Codeword Generation uses

Step 1: A simple histogram of the data is generated.

Character	Frequency
'0'	2760
'.'	947
'8'	446
...	...
'Y'	1

Table 5.4: Unique Character Histogram

In Table 5.4, each unique symbol's frequency is shown. As seen on the table, most used symbol is "0" and used 2760 times in electric meter's analytic data. Less frequent used symbol is capital "Y" and it is used once. That means Huffman's compression algorithm will assign shortest codeword to "0" symbol and "Y" will get the longest codeword.

Step 2: Huffman's algorithm generates new codewords for each character.

Character	Codeword
'0'	10
'.'	001
'8'	000000
...	...
'Y'	01101111111011

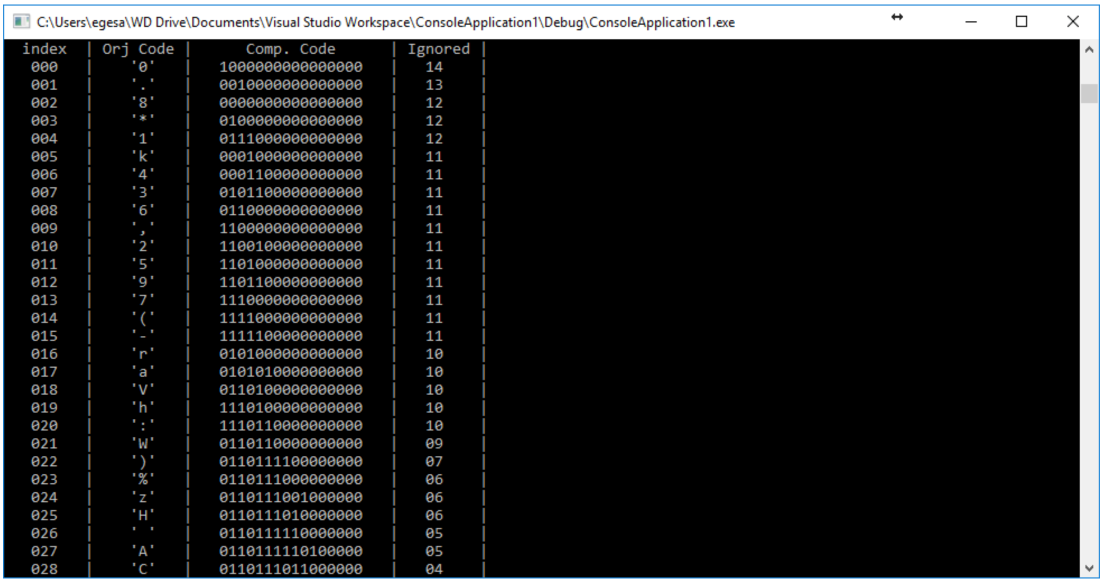
Table 5.5: Codeword Table

In Table 5.5 generated Huffman Codewords are shown. As mentioned before, "0" character is the most frequent symbol 5.4 and it gets the shortest codeword "10" which uses just two bits on memory. Character "Y" is less frequent symbol and Huffman algorithm assigned the longest codeword, which is "01101111111011" (14 bits long).

Step 3: Data is encoded with respect to the codeword table.

5.5 Simulation

A C64 program was written to test Compression Library on Visual Studio. Compression Ratio of %48 is achieved.



C:\Users\egesa\WD Drive\Documents\Visual Studio Workspace\ConsoleApplication1\Debug\ConsoleApplication1.exe

index	Orj Code	Comp. Code	Ignored
000	'0'	1000000000000000	14
001	'.'	0010000000000000	13
002	'8'	0000000000000000	12
003	'*'	0100000000000000	12
004	'1'	0111000000000000	12
005	'k'	0001000000000000	11
006	'4'	0001100000000000	11
007	'3'	0101100000000000	11
008	'6'	0110000000000000	11
009	','	1100000000000000	11
010	'2'	1100100000000000	11
011	'5'	1101000000000000	11
012	'9'	1101100000000000	11
013	'7'	1110000000000000	11
014	'('	1111000000000000	11
015	'-'	1111100000000000	11
016	'r'	0101000000000000	10
017	'a'	0101010000000000	10
018	'V'	0110100000000000	10
019	'h'	1110100000000000	10
020	':'	1110110000000000	10
021	'W'	0110110000000000	09
022	')'	0110111100000000	07
023	'%'	0110111000000000	06
024	'z'	0110111001000000	06
025	'H'	0110111010000000	06
026	' '	0110111110000000	05
027	'A'	0110111110100000	05
028	'C'	0110111011000000	04

Figure 5.4: Visual Studio Simulation

In Figure 5.4 screenshot of Visual Studio Simulation Program is shown. Symbol "0" is the most frequent, so that (Table 5.5) library assigned shortest keyword to it.

5.6 Optimization

5.6.1 Memory Optimization

Encoding and decoding processes allocates memory as large as the data which will be processed. In this implementation, compressed data size limited to 8KB and decompressed data size limited to 17KB. Operating system suspends other tasks, which are trying to access the library, while an on going compression or decompression process. With this optimization $17KB + 8KB = 25KB$ of memory always blocked in runtime.

5.6.2 CodeWord Table Optimization

Generally, electric meter data has 50 to 60 unique characters. Therefore, 128 lines (Table 5.3) is extremely larger than it is needed. First value of the header represents how many unique characters is used to compress the data (Section 5.4.3) and empty lines of the table can be skipped.

5.6.3 Repetitive Patterns in IEC62056

Further analysis showed that, units like *kVarh* , *kWh* etc. repeated lots of times. For example, every "k" symbols followed by an "V" or "W". Huffman's algorithm encodes every symbol individually, it does not find a connection between symbols. If we connect these symbols together, this should increase source codes entropy and also increase final compression performance.

String	Codeword	Frequency in RAW Data
"*kVarh)\r\n"	0x80	260
"*kVarh"	0x81	260
"*kWh)\r\n"	0x82	130
"*kWh)("	0x83	0
"*kW)\r\n"	0x84	6
"*kW)("	0x85	26
"\r\n"	0x86	579
")("	0x87	39

Table 5.6: Repetitive Patterns in Kohler AEL.TF.21

In Table 5.6, most frequent symbol group is *"\r\n"*, which is used 579 times in AEL TF 21's Read Out Data. Each string on the table 5.6 replaced with assigned codeword before compression progress, which saves nearly 1KB per read out.

Chapter 6

Results and Discussion

Primary goal of this study is reducing the internal storage of DR-502-DCL model Electric Meter Reader. Minimum required memory is decreased from 32 Megabytes to 16 Megabytes. Total cost of the design is decreased 0.5$ per device. Compression library uses 11 Kilobytes on program memory and 25 Kilobytes on RAM. Each encode/decode process done one by one for minimizing RAM usage.

Huffman's algorithm compressed the meter data by %45-49 percent without any optimization. Generally this is enough for routine usage of the modem. However, AEL.TF.21's (Table 5.1) excessive data size takes up too much space even though %45 percent compression rate. With header and repetitive pattern optimization %57 percent compression achieved. Main goal, which is compressing 16 electric meters' 2 months of data into 15MB (Chapter 3, Section 4.1.2), is achieved. In total 16 electric meters can be logged for 2 months on 15 Megabyte space.

Additional optimization improved total compression rate up to 8% percent.

Brand	Model	RAW	Huffman w/o Opt.	Huffman w/ Opt.	WinZip
Kohler	AEL.TF.20	10913	5694 (CR* %48)	4851 (CR* %56)	2934 (CR* %73)
Kohler	AEL.TF.21	16605	9087 (CR* %45)	7137 (CR* %57)	3119 (CR* %81)
Luna	LUN4/5	1721	911 (CR* %47)	775 (CR* %56)	580 (CR* %66)
Makel	MSY.C410	6551	3403 (CR* %48)	3012 (CR* %54)	1403 (CR* %78)
Makel	MSYC500	6584	3545 (CR* %46)	2897 (CR* %56)	1345 (CR* %80)
Viko	VEMC	9326	4755 (CR* %49)	3916 (CR* %58)	1961 (CR* %78)

Table 6.1: Huffman Compression without Optimization, Huffman Compression with Optimization, and WinZip's Compression Applied to RAW Data. (Values are in Terms of Bytes)(*Compression Ratio)

In Table 6.1 six different electric meters' Read out data sizes and their compression performances compared with WinZip. WinZip uses heuristic methods and more complex algorithms to achieve this performance. These algorithms requires much larger memory space that a micro-controller can have. Therefore, these algorithms is not practical to use on a micro-controller Kohler AEL.TF.21 Model Electric Meter produced 16605 bytes of read out data. With Huffman Compression data compressed into 7137 bytes. Compression ratio of %57.01 is achieved with Optimized Huffman compression method.

AEL TF 20 Read Out Data	Uncompressed	Compressed w/o Optimization	Compressed w/ Optimization
Data Size (bytes)	10913	5694	4851
Entropy (bits/symbol)	4.1500	7.5823	7.6509

Table 6.2: AEL TF 20 Compression Performance Table

In Table 6.2, Kohler AEL.TF.20 electric meter's read out data compression performance is shown. Just Huffman's compression algorithm can compress AEL.TF.20's Read Out data by %48 percent. If optimization is used, same data can be compressed by %56 percent. When data is more compressed and dense, it's entropy goes up an reaches to its final limit to 8 bits/symbol. Optimization increased performance by %15 percent, and increased entropy by %0.9 percent.

In Appendix B, memory snap of micro-controller can be seen. AEL.TF.20 model electric meter's uncompressed raw data length is 10913 bytes. When not optimized Huffman Compression is applied to RAW data (Appendix C) compression ratio of %47.96 is achieved and RAW data is reduced to 5679 bytes. Moreover, optimized Huffman compression is applied to AEL.TF.20's RAW data (Appendix D) compression ratio of %59.40 is achieved and RAW data is reduced to 4413 bytes. Each compression process uses different RAW data, therefore compression ratio can be slightly higher or lower than other ones. However, optimized Huffman Compression algorithm always results better performance than Huffman compression itself.

In future, a simple pattern recognition algorithm can be added to reorganize repetitive patterns to compress data [16]. Also header section can be represented more briefly to cover much more smaller space. From another standpoint, electric meter data can be parsed and logged on a pre-defined map as integer values, which will decrease data length much more smaller and increase its entropy. If parsing method is combined with a more efficient method like *Arithmetic Coding* [17] compression ratio can be better than WinZip's [18] ratio.

Chapter 7

Conclusion

Advanced Metering Infrastructure is a data measurement and collection architecture. AMI uses smart meters, communication networks, and data management systems. AMI system can be used as a Automated Meter Reading (AMR). Electric Distribution Companies (or Power Companies) uses this collected data for billing, estimate future usage trends, and loads on interconnected electric grid.

This study showed that, compression algorithms will improve memory usage. Huffman Compression Algorithm (Section 5.3) compressed sample data to %48. Combining adjoining symbols increased Huffman's performance by %15 Final compression ratio became %58-59.

When RAM usage of embedded systems is considered, memory management is crucial. Compression library's memory space is allocated at the beginning of the execution and maximum size of the compressed data size is limited to 25 KB. This study showed that compression algorithms can be implemented with static heap memory strategy and perform compression over and over again without any stack-overflow.

An entropy coding can decrease required memory size by a factor of 2. Although compressed logs can be transferred over RF or Power-line with lower bandwidths. New technologies like NB-IOT [19] will increase GSM tower's capacity to 5000 clients and double the range with lower bandwidth. Main idea is to maintain IOT devices' internet connectivity over GSM network. For this reason compression algorithms became more of an issue. Today in Turkey none of the electric distribution companies uses data compression for transferring consumer's consumption data. In the near future compression will be mandatory for IOT devices.

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Appendix A

AEL.TF.21 RAW Data

/AEL5¡1¿AEL.TF.21

0.0.0(21000028)

0.1.0(28)

0.1.2*1(16-01-01,00:00)

0.1.2*2(15-12-01,00:00)

0.1.2*3(15-11-01,00:00)

0.1.2*4(15-10-01,00:00)

0.1.2*5(15-09-01,00:00)

0.1.2*6(15-08-01,00:00)

0.1.2*7(15-07-01,00:00)

0.1.2*8(15-06-01,00:00)

... 560 more lines ...

97.97.0(00)

97.97.0*1(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*2(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*3(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*4(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*5(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*6(00-00-00,00:00,00-00-00,00:00,00)

97.97.0*7(00-00-00,00:00,00-00-00,00:00,00)

!

Appendix B

AEL.TF.20 RAW Data Size and Memory View

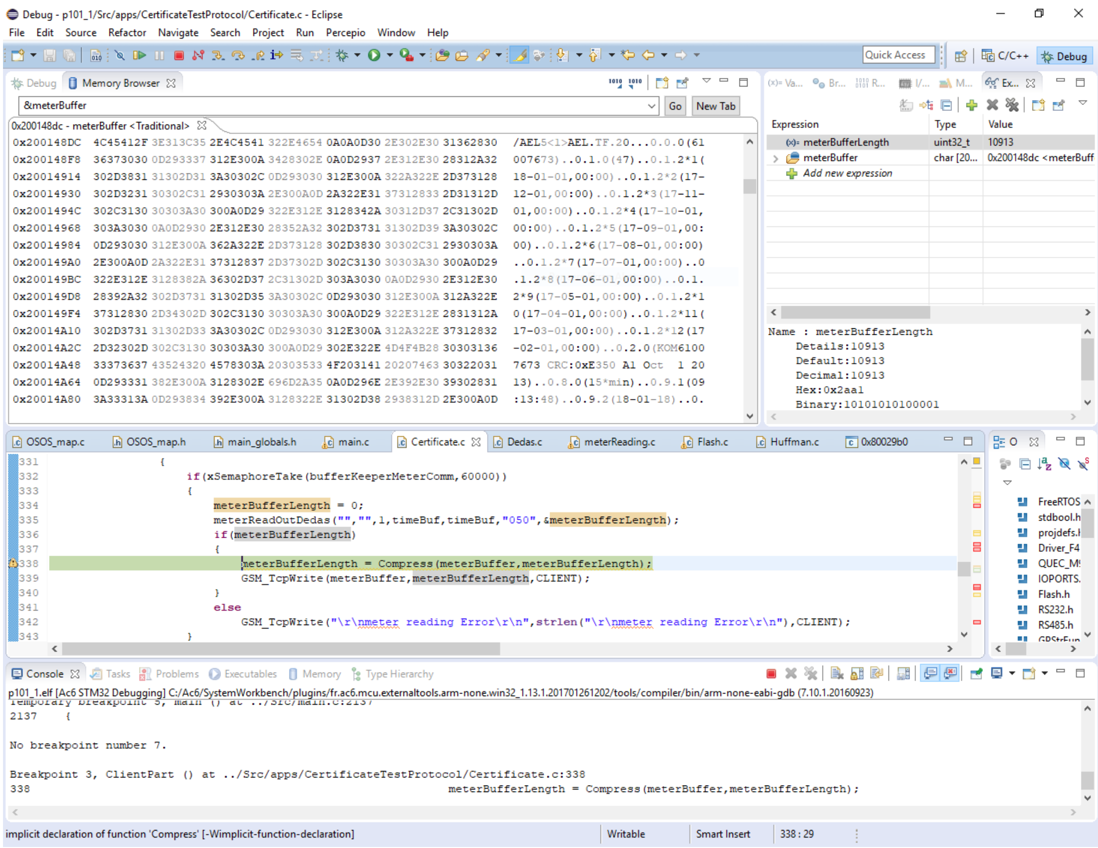


Figure B.1: AEL.TF.20 RAW Data Size and Memory View

Appendix C

AEL.TF.20 Huffman Compressed Data Size and Memory View

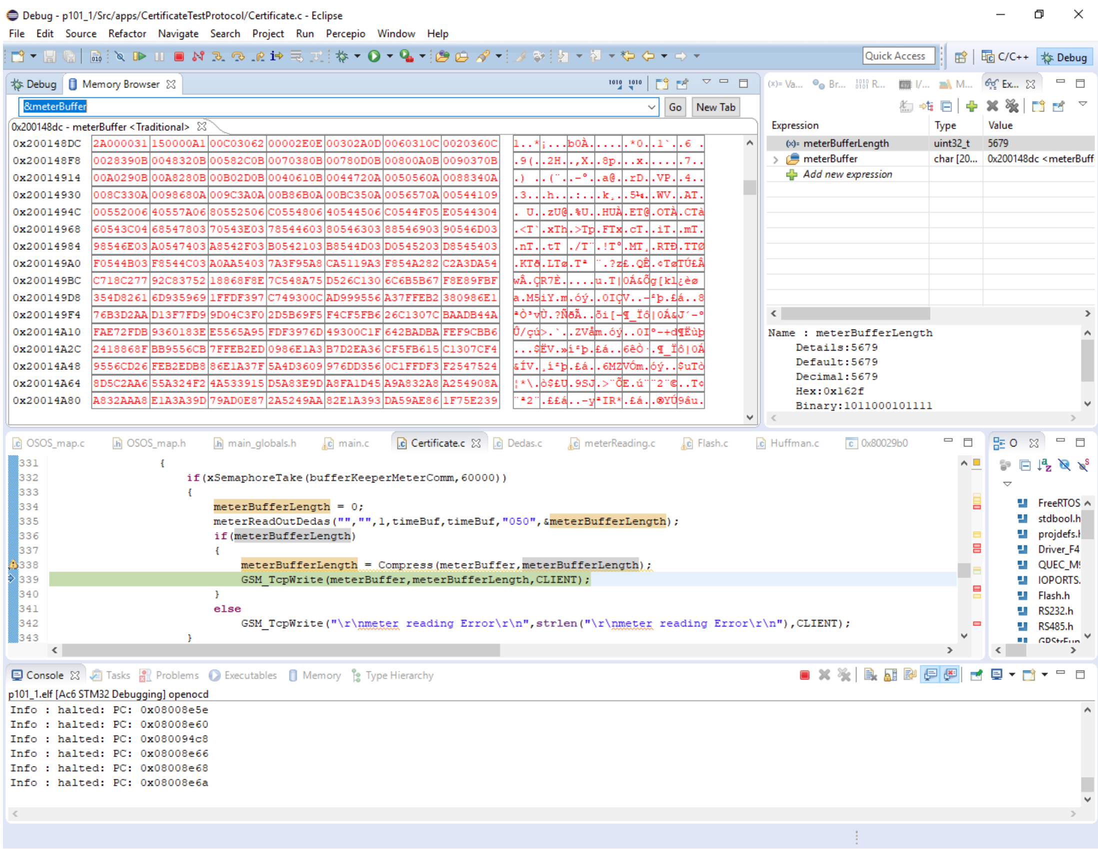


Figure C.1: AEL.TF.20 Huffman Compressed Data Size and Memory View

Appendix D

AEL.TF.20 Huffman Optimized Compressed Data Size and Memory View

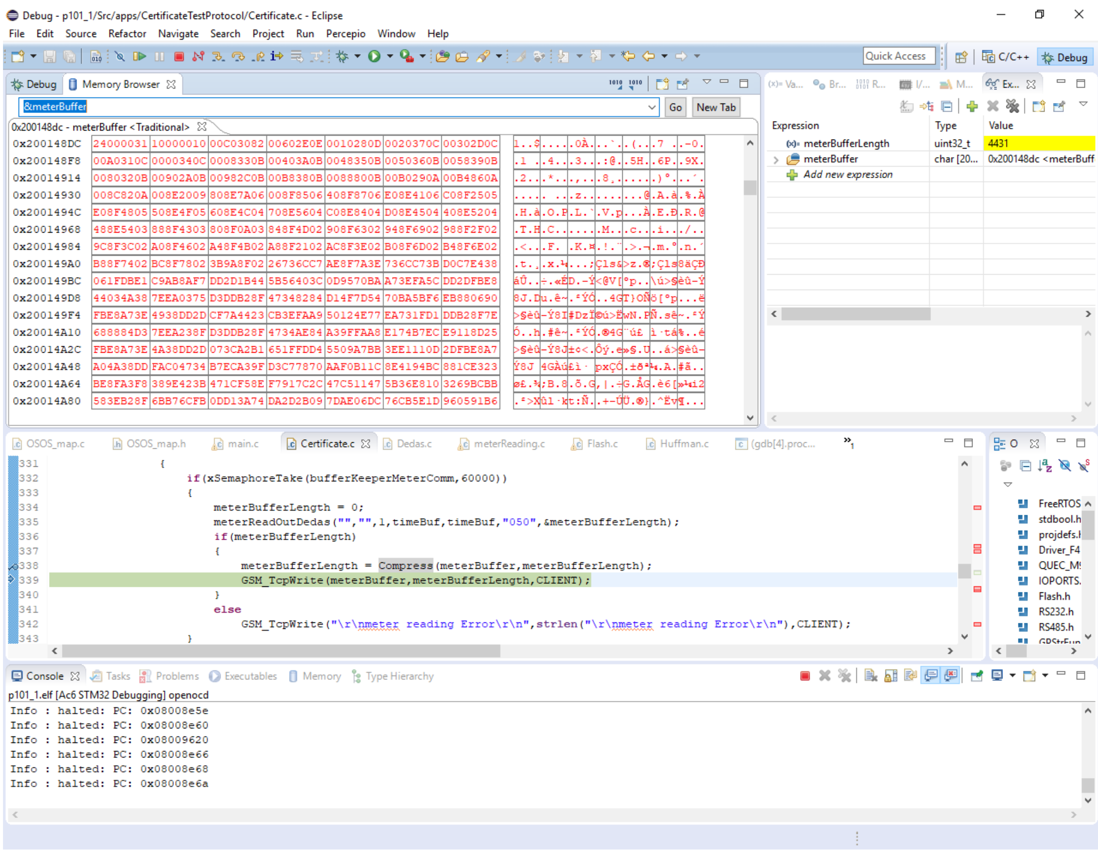


Figure D.1: AEL.TF.20 Huffman Optimized Compressed Data Size and Memory View

Appendix E

DEDAS Terms of Reference

Next 5 pages are Dicle Electric Distribution Company's Automated Meter Reading Unit's Auction Terms in Turkey (2017).

DİCLE ELEKTRİK DAĞITIM A.Ş.

OSOS – GSM Modem Teknik Şartnamesi

2017-Mayıs

AMAÇ

Bu teknik şartnameyle, Dicle Elektrik Dağıtım A.Ş. hizmet bölgesinde bulunan dağıtım şebekesi dâhilindeki piyasa katılımcılarına kurulacak Otomatik Sayaç Okuma Sisteminin haberleşme ünitesinin teknik gereksinimleri belirlenmiştir.

DONANIM ÖZELLİKLERİ

1- Haberleşme Ünitesinin sahip olduğu haberleşme modülü takılıp çıkarılabilir yapıda olmalıdır. (Opsiyonel)

2- Haberleşme Modülü Dual Band / Quad Band haberleşme kanalı üzerinden haberleşebilmelidir. Modüler bir yapıya sahip olmalı, LTE, 3G, 4.5G ve daha yeni teknolojilere geçiş sağlayabilmelidir. (Opsiyonel)

3- Haberleşme ünitesi (Modem), enerji kesinti bilgilerini AKM ye iletebilecek şekilde desteklenmiş Pil ya da Süper kapasitör bulundurmalıdır. En az 5 dakika modemi besleyecek kapasitede olmalıdır.

4- Güç, GSM Sinyal Seviyesi, AKM bağlantısını ifade edebilecek LED göstergelerine sahip olmalıdır.

5- Head End ile bağlantı kurulamaması durumlarında kendi içerisinde bulunan hafızasında bilgileri saklayarak, bağlantı kurulduğunda ilgili verileri AKM Sistemine göndermelidir. Burada veri saklama kapasitesi 2 ay dan az olmamalıdır. (16 Sayaç için).

6- Klemens kapağı mühürlenebilir olmalıdır.

7- Haberleşme klemens uçları (RS-485) ile besleme klemens uçları birbirinden farklı olmalı ve haberleşme portlarına enerji verilmesini engelleyecek nitelikte olmalıdır.

8- Haberleşme ünitesi, besleme bacaklarında 435 Volt gerilimin atlamalarına karşı enerji giriş pinlerinde gerekli mesafeyi korumalıdır.

9- Gerçek zaman saati bulundurmalı, NTP server ile haberleşerek kendi saatini düzenleyebilme kapasitesine sahip olmalıdır. Gerçek zaman saati pil ile beslenmelidir.

10- Haberleşme ünitesi kendi kendisine periyodik olarak HARD RESET atabilmelidir. Bu hard reset cihaz üzerinde bulunan tüm komponentlerin resetlenmesi (Enerjisinin belirli bir süre kesilip tekrar verilmesi) şeklinde olmalıdır.

11- Haberleşme ünitesi (Modem) elektromanyetik etkiye karşı izolasyonlu olup, test ortamında manyetik alanlara karşı test sonuçları belgelenmelidir. Belirli bir manyetik sınıra karşı dayanıklı olmalıdır.

12- RS-485 uçlarının (A-B) ters bağlanması durumunda, modem sayaç ile bu durumda da iletişim kurabilmelidir. (Opsiyonel)

13- Tedarikçi firma, talep edildiğinde anten gücüne ek olarak bedelsiz yüksek kazançlı(10dB) anten temini yapmalıdır. Anten kazançlarının test sonuçları belgelenmelidir. (Opsiyonel)

14- İzoleli 1 adet Dijital Giriş bulunmalı, 6kV darbe dayanımına sahip olmalıdır.

15- İzoleli 1 adet röle çıkışı bulunmalıdır. (250 VAC, asgari 3.5 amper)

16- Asgari UL 90 V0 yanmazlık sınıfına sahip olmalıdır.

17- Haberleşme ünitesi harici güç beslemesi kullanmamalıdır.

18- Haberleşme ünitesi 85-435 VAC gerilim aralığında çalışabilmelidir. Bu gerilim seviyesine ulaşıldığında modem kendisini koruyucu komponentler ile korumalıdır.

19- Haberleşme ünitesi kendisini yüksek gerilime karşı sigorta ile korumalıdır. Yüksek gerilim nedeni ile yaşanacak haberleşme birimi değişimleri toplam alım miktarının %5'i ni aşmayacak şekilde tedarikçi tarafından bedelsiz yapılacaktır.

20- 50 +- %5 Hz frekansta çalışabilmelidir.
21- Haberleşme ünitesi, diagnostik testlere tabii tutulabilmesi için devre kartı üzerinde test pointleri bulundurmalıdır.
22- Haberleşme Ünitesi üzerinde bağlantı bilgileri gösterilmelidir. (RS, Enerji, Input, Output klemensleri)
23- Ray ve Düz montaj a uygun olmalıdır.
24- Haberleşme Ünitesi giriş sigortasının arızasında sahada değiştirilebilir veya anlaşılabilir yapı da olmasının sağlanması veya modem sigorta yanma durumunun yazılımda diğer arızalarından ayırt edilmesi sağlanmalıdır. (Opsiyonel)
25- Haberleşme ünitesi üzerinde dahili GPS modülü bulundurmalı, koordinat bilgileri AKM yazılımına gönderilmelidir. (Opsiyonel)

FONKSİYONEL ÖZELLİKLER

1- Pull Push çalışma özelliği sunmalıdır.
2- Haberleşme ünitesi kendisine AKM tarafından verilen anlık okuma isteklerine yanıt vermelidir.
3- Haberleşme ünitesi kendisi üzerine tanımlanan zamanlanmış görevleri işletebilmeli ve istenen zamanda AKM'ye gönderebilmelidir.
4- Haberleşme Ünitesine anlık Röle aç / kapat emirleri verilebilmelidir.
5- Haberleşme ünitesi zamanlanmış görevler ile röle aç/kapa işlemlerini yapabilmelidir.
6- SMS ile resetleme, APN ayarlama özelliklerine sahip olmalıdır.
7- Modem enerji kesilme bilgisini AKM yazılımına iletebilmelidir.
8- AKM yazılımına, sinyal seviyesi, Sim Kart numarası, bağlanılan GSM Baz istasyonunun GPS koordinatı gibi bilgileri gönderebilmelidir.
9- Haberleşme üniteleri uzaktan ve toplu halde güncellenebilir olmalıdır.
10- Haberleşme ünitelerinin APN bilgileri uzaktan güncellenebilmelidir. Bu güncelleme firmware den bağımsız olarak konfigürasyon paketi ile sağlanabilmeli ve bu güncelleme işletme tarafından sağlanabilmelidir.
11- Başarıyla tamamlanamayan ve kesilen erişimlerin kaydını tutabilmeli ve AKM sistemine gönderebilmelidir.
12- Haberleşme üniteleri uzaktan izlenebilmeli ve modem üzerinde gerçekleşen işlemler takip edilebilmelidir. İzleme modeme erişilip ilgili izleme şifresi girildikten sonra sağlanmalıdır.
13- Veri haberleşmesinde veri sıkıştırmaya izin vermelidir.
14- Resetlenme sonrasında AKM ile otomatik olarak iletişime geçebilmelidir.
15- Mobil şebekenin veri aktarım hızlarına uyum sağlamalı ve değişimlerine göre çalışabilmelidir.
16- İlgili röle çıkışı modemin resetlendiği durumlarında pozisyonunu koruyabilmelidir.

17- Okunacak sayaca göre otomatik Baudrate ayarlaması yapabilmelidir.
18- Sayaç iletişim protokolü olarak IEC62056-21 Mod A/B/C DLMS ve COSEM haberleşmeye izin vermelidir.
19- Haberleşme Ünitesi, işletmenin belirleyeceği protokol yapısına uygun olarak modemleri teslim etmelidir.
20- Modem sayaçlardan aldığı verilerin doğruluğunu teyit edebilmeli gerekiyorsa yeniden sayaçtan veri almalıdır.

GÜVENLİK & SERTİFİKALAR

1- Modem EMC ve ESD test sonuçları paylaşılmalıdır.

2- CE/TSE/ISO Sertifikası bulunmalıdır.
3- Tedarikçi işletmenin izni ve onayı olmaksızın haberleşme üniteleri üzerindeki yazılımları güncellememelidir.
4- EPDK Asgari Şartlarına uyumlu olmalıdır.
5- Yetkisiz erişimleri engellemeli ve izin verilen IP adresi dışında bağlantıya izin vermemelidir. Yetkisiz erişim girişimleri cihaz tarafından LOG lanmalı ve haberleşme ünitesi bu girişimi AKM sistemine gönderebilmelidir.
6- Modem üzerinde Sistem ve Olay kayıtlarını tutabilmeli periyodik olarak ya da istendiğinde AKM yazılımına gönderebilmelidir.
7- Veri haberleşmesinde şifrelemeye izin vermelidir. SCP, Secure SSL, AES, RSA, DES, 3DES şifreleme yöntemlerinden en az birini desteklemeli ve istendiğinde aktifleştirilebilmelidir.
8- Haberleşme ünitesi istendiğinde transparan mod özelliği sunabilmelidir. Merkezi sistemden el ile gönderilecek komutları işleme kapasitesine sahip olmalıdır.
9- Asgari IP 54 Koruma seviyesine sahip olmalıdır.
10- Haberleşme Ünitesi üzerinde bulunan tüm komponentler endüstriyel nitelikte olmalı ve -40 / +70 derecede sorunsuz çalışmalıdır.
11- Bağlı bulunduğu sayacın maruz kaldığı çevresel koşullara karşı dayanıklı olmalıdır.

DİĞER ÖZELLİKLER

1- Her marka elektronik elektrik sayacını okuyabilmelidir. Tedarikçi, işletmenin talep etmesi durumunda yeni marka ve model sayaçların modem ile okunabilmesini maximum 15 iş günü içinde sağlamalıdır. Bu süreyi aşan her bir gün için cezai şart konulacaktır.
2- Yeni marka ve model sayaçların yazılım entegrasyonlarının yapılabilmesi için modem sahibi firma sayaçları kendisi temin edecektir. İşletmenin sayaç temini gibi bir zorunluluğu yoktur.
3- Teknik Özellikler ve Kurulum Kılavuzu sunulmalıdır.
4- Yazılım ve Donanım bilgilerinin tümü işletmeye verilecektir.
5- Türkiye’de bulunan GSM operatörleri ile çalışabilmelidir.
6- GSM şebekelerinde kullanılabilmesi için ilgili kurumlardan gerekli izinler ve onaylar alınmış olmalıdır.

7- 10 Yıl kullanım ömrüne sahip olmalıdır.
8- Modemlerin üzerine Şirketin istemiş olduğu özelliklere sahip QR kod basılacaktır.

GARANTİ VE DESTEK FAALİYETLERİ

1- Haberleşme üniteleri için tedarikçi firmalar mal teslimlerinde garanti belgelerini ibraz etmelidir.

2- Kullanıcı hataları dışında asgari 3 yıl garantiye sahip olmalıdır.
3- Ürünlerin arızalı olarak firmaya tesliminde 15 gün içerisinde modemin onarılıp ya da gerekçesi bildirilerek tarafımıza iadesi yapılmalıdır. Bu sürelerin uzaması durumlarında cezai şartların sözleşmede belirtilmesi ve cezaların işletilmesi.
4- Modem yazılımlarında (firmware) üzerinde ortaya çıkan sorunların çözümünde sorunun bildirilmesinden sonraki en geç 15 gün içinde sorunun çözülmesi sürenin uzaması durumu için cezai şartların sözleşmeye eklenmesi.
5- Sözleşme süresince, yeni tip sayaçların işletme tarafından sisteme eklenmesi durumunda, ilgili sayaç driverlarının modemlere eklenmesinin, tedarikçi firmaya bildirilmesinden itibaren 15 gün içerisinde tamamlanması aksi takdirde sözleşmeye cezai şartların eklenmesi.

6- Saha montajlarının yapılmasından sonra, sahadaki sayaç okumasının modem donanım arızasından dolayı kesildiği tespit edildiğinde, toplam proje maliyetinin %15 ini aşmayacak şekilde işçilik maliyetlerinin tedarikçi firmaya rücu edilmesi. Sahada okuma yapamayan ve veri gönderemeyen modemler Tedarikçi Firma ve İşletmenin belirleyeceği bir ekip ile kontrol edilip sonuçlarının tutanak altına alınması ile gerçekleşir.

TESTLER

1- Tedarikçi, işletmeye, haberleşme ünitesi ile ilgili yapılması gereken testlerin nasıl yapılacağını ayrıntılı olarak anlattığı bir doküman paylaşacaktır.
2- Kabul testleri İşletmenin ve Tedarikçinin belirleyeceği en az 2 kişilik kabul ekibi ile gerçekleştirilecektir.
3- Tedarikçi, satış sonrasında kullanılmak üzere, haberleşme ünitelerinin testlerinin İşletme tarafından yapılabilmesi için iki test masası kuracaktır (diagnostik ve fonksiyonel). Bu masa, haberleşme ünitesi üzerinde bulunan test noktalarını analiz edebilecek bir diagnostik test cihazı olmalıdır. Kurulacak noktalar işletme tarafından belirlenecektir. Masaların kullanımı için işletmenin belirlediği en az 2 kişiye tedarikçi tarafından eğitim verilecektir.
4- Tedarikçi, test aşamalarında gerekli olacak teçhizat, yazılım ve araç gereci bedelsiz olarak temin etmelidir.

5- Modem test sürecinde ilk testten sonra modemlerin hazır olmadığı tespit edilecek olur ise, sonraki yapılacak testlerde ortaya çıkacak seyahat ve konaklama masrafları tedarikçi tarafından karşılanacaktır. Seyahat ve konaklama özellikleri işletmenin seyahat ve konaklama politikalarına uygun şekilde yapılacaktır.

DOKÜMANTASYON

1- Tedarikçi tarafından işletme personeline kılavuz olarak kullanabileceği el kitapçığı hazırlayacaktır.
2- Kılavuz içeriğinde detaylı bir şekilde montaj, sökme, bakım ve özel öneriler bulunacaktır.
3- Kılavuz Türkçe hazırlanmış olmalıdır.
4- Kılavuz incelenip onaylanması için İşletmeye dokümanı teslim edecek, işletme tarafından onaylanmasından sonra dijital ve matbu olarak 3 şer nüsha halinde işletme ile paylaşılacaktır.

TANIMLAR

- **İşletme** : Dicle Elektrik Dağıtım A.Ş.
- **Tedarikçi** : Şartnameye konu olan iş için sözleşme imzalayan gerçek veya tüzel kişi.
- **APN** : Access Point Name
- **AKM** : Ana Kontrol Merkezi

Appendix F

STM32F412 Specifications

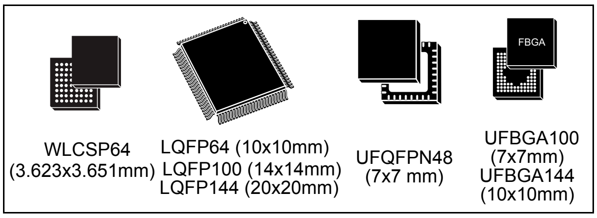
STM32F412xE STM32F412xG

ARM®-Cortex®-M4 32b MCU+FPU, 125 DMIPS, 1MB Flash, 256KB RAM, USB OTG FS, 17 TIMs, 1 ADC, 17 comm. interfaces

Datasheet - production data

Features

- Dynamic Efficiency Line with BAM (Batch Acquisition Mode)
- Core: ARM® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator™) allowing 0-wait state execution from Flash memory, frequency up to 100 MHz, memory protection unit, 125 DMIPS/1.25 DMIPS/MHz (Dhrystone 2.1), and DSP instructions
- Memories
  - Up to 1 Mbyte of Flash memory
  - 256 Kbyte of SRAM
  - Flexible external static memory controller with up to 16-bit data bus: SRAM, PSRAM, NOR Flash memory
  - Dual mode Quad-SPI interface
- LCD parallel interface, 8080/6800 modes
- Clock, reset and supply management
  - 1.7 V to 3.6 V application supply and I/Os
  - POR, PDR, PVD and BOR
  - 4-to-26 MHz crystal oscillator
  - Internal 16 MHz factory-trimmed RC
  - 32 kHz oscillator for RTC with calibration
  - Internal 32 kHz RC with calibration
- Power consumption
  - Run: 112 µA/MHz (peripheral off)
  - Stop (Flash in Stop mode, fast wakeup time): 50 µA Typ @ 25 °C; 75 µA max @25 °C
  - Stop (Flash in Deep power down mode, slow wakeup time): down to 18 µA @ 25 °C; 40 µA max @25 °C
  - Standby: 2.4 µA @25 °C / 1.7 V without RTC; 12 µA @85 °C @1.7 V
  - V_{BAT} supply for RTC: 1 µA @25 °C
- 1×12-bit, 2.4 MSPS ADC: up to 16 channels
- 2x digital filters for sigma delta modulator, 4x PDM interfaces, stereo microphone support
- General-purpose DMA: 16-stream DMA



- Up to 17 timers: up to twelve 16-bit timers, two 32-bit timers up to 100 MHz each with up to four IC/OC/PWM or pulse counter and quadrature (incremental) encoder input, two watchdog timers (independent and window), one SysTick timer
- Debug mode
  - Serial wire debug (SWD) & JTAG
  - Cortex®-M4 Embedded Trace Macrocell™
- Up to 114 I/O ports with interrupt capability
  - Up to 109 fast I/Os up to 100 MHz
  - Up to 114 five V-tolerant I/Os
- Up to 17 communication interfaces
  - Up to 4x I^2C interfaces (SMBus/PMBus)
  - Up to 4 USARTs (2 x 12.5 Mbit/s, 2 x 6.25 Mbit/s), ISO 7816 interface, LIN, IrDA, modem control)
  - Up to 5 SPI/I2Ss (up to 50 Mbit/s, SPI or I2S audio protocol), out of which 2 muxed full-duplex I2S interfaces
  - SDIO interface (SD/MMC/eMMC)
  - Advanced connectivity: USB 2.0 full-speed device/host/OTG controller with PHY
  - 2x CAN (2.0B Active)
- True random number generator
- CRC calculation unit
- 96-bit unique ID
- RTC: subsecond accuracy, hardware calendar
- All packages are ECOPACK®2

Table 1. Device summary

Reference	Part number
STM32F412xE	STM32F412CE, STM32F412RE, STM32F412VE, STM32F412ZE
STM32F412xG	STM32F412CG, STM32F412RG, STM32F412VG, STM32F412ZG