PERFORMANCE AND ENERGY EFFICIENCY OF COMMON COMPRESSION/DECOMPRESSION UTILITIES: AN EXPERIMENTAL STUDY IN MOBILE AND WORKSTATION COMPUTER PLATFORMS

by

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ABSTRACT

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Title Performance and Energy Efficiency of Compression/Decompression Utilities: An Experimental Study in Mobile and Workstation Computer Platforms

Lossless compression and decompression are routinely used in mobile and workstation computer systems to reduce the costs of communicating and storing data. This research presents the results of a measurement-based experimental evaluation of common compression and decompression utilities running on several platforms of varying hardware complexity representing current mobile and workstation systems. The evaluation involves characterization of the compression and decompression utilities in a multi-dimensional space encompassing the compression ratio, compression and decompression throughput, and energy efficiency. Different use scenarios and conditioning typical for modern mobile and workstation computing platforms are considered. The study observes a wide variety of energy costs associated with data compression and decompression and provides practical guidelines for selecting the most energy efficient configurations for each system and use scenario considered.

Abstract Approval: Committee Chair _____

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CHAPTER 1

INTRODUCTION

An exponential growth of the Internet traffic and emergence of mobile computing platforms with limited storage and energy resources make data compression and decompression crucial as they can reduce communication latencies and make effective use of the available storage. A number of compression utilities have been developed and routinely used in many areas of computing. In this thesis we focus on lossless compression and decompression, critical for all non-audio or non-video based digital content. Whereas common lossless compression and decompression utilities are well-understood as far as their performance and compression ratios are considered, little is known about their energy efficiency. The goal of this thesis is explore energy-efficiency of common utilities in typical use scenarios of mobile and desktop computing. The rest of the Introduction section gives background and motivation, discusses data compression, describes work done in the thesis, lists contributions of this thesis, and gives the outline of the rest of the thesis.

1.1 Background and Motivation

The total number of computing devices has been increasing substantially in recent years, mainly due to unprecedented proliferation of mobile computing devices. Mobile devices such as smartphones, tablet computers, and e-readers have steadily been gaining market share, dethroning laptop and desktop computers as dominant personal computing platforms. According to an estimate for 2011 [1], vendors

shipped 487.7 million smartphones (up 63% from the year before) and 67 million tablets (up 274%), whereas the number of notebooks and desktop computers shipped was 209.6 million (up 7.5%) and 112.4 million (up 2.3%), respectively. A more recent estimates report a record 700 million smartphones shipped (up 43% from the year before) in 2012 [2], and 383 million of personal and desktop computers (notebooks and desktop computers combined) was estimated to be sold [3]. It is forecasting that the number of smartphones and tablets shipped in 2015 will reach 1.4 billion and 326 million, respectively [1], whereas the number of personal computers shipped in 2015 will reach 490.6 million [3].

The amount of data traffic initiated from mobile devices has been growing rapidly as well. A report from Cisco states that the global data traffic for mobile devices alone grew 2.3-fold in 2011, reaching 597 petabytes per month, which is over 8 times greater than the total Internet traffic in 2000 [4].

Energy efficiency is becoming an important design requirement for mobile and workstation platforms alike. For mobile devices, it is driven by several key factors, including (i) limited energy capacity of batteries, (ii) cost considerations favoring less expensive packaging, and (iii) user convenience favoring lightweight designs with small form factors that operate for long periods without battery recharges. For workstations and servers, it is driven specifically by the desire to reduce the operating costs of data centers. However, the greener outlook on energy consumption is also taken often by device manufacturers of desktop, laptop, and ultrabook computers.

With current trends, where data traffic is increasing and large consumption of digital information is observed on mobile devices with limited storage and energy resources, minimizing storage capacity requirements and energy costs of data communication is of great interest for both mobile devices and workstations in data cen-

ters that make consumption of data available. Data compression utilities are thus critical in achieving energy-efficient data communication, reducing communication latencies and making effective use of available storage.

1.2 Data Compression

The general goal of data compression is to reduce the number of bits needed to represent information. Data can be compressed losslessly or lossily. Lossless compression means that the original data can be reproduced exactly by the decompressor. In contrast, lossy compression, which often results in much higher compression ratios, can only approximate the original data. This is typically acceptable if the data are meant for human consumption such as audio and video. However, program code input, medical data, email and other text do not tolerate lossy compression. This thesis focuses on lossless compression only for this research.

Lossless compression is achieved by replacing frequent bit or byte strings with shorter sequences and infrequent bit or byte strings with longer sequences, which tends to reduce the overall data size. For example, in Huffman compression, bit strings are assigned unique, variable-length code words whose length is inversely proportional to the frequency of the corresponding bit strings. Huffman coding [5], or the slower but more sophisticated arithmetic coding [6], is often preceded by a transformation stage whose purpose it is to model (or predict) the data. If the model is good, i.e., accurate, then the difference sequence between the predicted and the actual data primarily consists of small values that cluster around zero, which are easy to encode effectively. Various models are in use, including dictionaries of expected or recently encountered “words,” sliding windows that assume that recently seen data patterns will repeat, which are used in the Lempel-Ziv approach [7], as well as re-

versibly sorting data to bring similar values close together, which is the approach taken by the Burrows and Wheeler transform [8]. The data compression algorithms used in practice combine different models and coders, thereby favoring different types of inputs and representing different tradeoffs between speed and compression ratio. Moreover, they typically allow the user to select the dictionary, window, or block size through a command-line argument.

The choice of algorithm, compression level, and the quality of the implementation also affect the energy consumption. This aspect is not critical on desktop PCs and workstations, but it can be a decisive factor in battery-powered handheld devices. In fact, it is reasonable to assume that achieving a higher compression ratio requires more computation and therefore energy, but better compression reduces the number of bytes, thus saving energy when transmitting the data. Hence, it is beneficial to take a close look at the energy-efficiency of lossless compression algorithms across systems of varies hardware complexity, such as state-of-the-art mobile and workstation platforms that communicates over the network. In particular, answers to whether compression is useful for reducing energy consumption, which common compression algorithms should be used, what configurations result in the best energy efficiency, and whether parallel execution can save energy are needed.

1.3 What has been done?

In this thesis, a comparative study of the most recent versions of several popular compression utilities, including gzip, lzop, bzip2, xz, pigz (a parallel implementation of gzip) and pbzip2 (a parallel implementation of bzip2) are performed on several contemporary computing platforms. Platforms include Pandaboard, a state-of-the-art mobile development platform, Raspberry Pi, a low-end mobile computer plat-

form, and a Dell Precision T1600 workstation. For each utility, the effectiveness of all supported compression levels is analyzed to provide a complete picture. Common performance metrics such as compression ratio and compression and decompression throughputs are examined. Energy-efficiency metrics are introduced and the energy consumed by compression and decompression tasks is studied using our experimental setup for energy measurements. To study effects of frequency scaling on Pandaboard and the workstation platform, the experiments are repeated for each frequency step. Pandaboard supports four frequency steps, 300MHz, 600MHz, 800MHz and 1.01GHz. The workstation platform supports ten frequency steps for each core from 1.60GHz to 3.40GHz.

The compression utilities evaluated in three typical use scenarios. The Local experiment involves compression and decompression tasks performed locally on system under test (Pandaboard/Raspberry Pi/Workstation). The Wired and Wireless experiments involve compression tasks that stream data to and from a remote server over a secure communication channel. The Wired experiment uses an Ethernet network interface, and the Wireless experiment uses a wireless LAN interface. Compression utilities for Raspberry Pi and Workstation are evaluated only for the Local and Wired experiment for reasons of not having native wireless adapter. Only Pandaboard, with single-chip platform WiLink™ 6.0 provides wireless LAN natively [9].

The main findings of research are as follows.

- The effectiveness of compression utilities varies widely across different utilities and compression levels, often spanning two orders of magnitude.
- For local compression and compression with upload over the wired network, the fastest utility, lzop with compression levels -1 to -6, performs

the best in both compression throughput and energy efficiency. The next best utility is pigz with low compression levels.

- For local decompression, lzop performs the best.
- For decompression after download over the wired network, pigz, gzip, and lzop perform the best, regardless of the compression level that was used for generating the input files.
- For compression with upload over the wireless interface, pigz and gzip with low compression levels (-1 to -4) perform the best.
- For decompression after download over the wireless network, xz with the highest compression level achieves the best decompression throughput and energy efficiency.

Whereas similar studies has been conducted almost a decade ago [10]–[12] for mobile platforms and a similar one for workstation and server platforms [13], our work complements the prior studies. Setup in thesis supports more accurate energy measurements (both hardware based and software based with the help of Intel on-chip power meter), considers the most recent compression utilities including some with parallel implementations and uses three state-of-the-art platforms that represent modern mobile devices and workstation platforms. In addition, this study provides performance and energy efficiency data for all supported compression levels, in three typical use scenarios with representative modern datasets and for all frequency levels that are supported on the selected platforms.

1.4 Contributions

This thesis makes the following contributions to the field of measurement-based power profiling and to the field of compression and decompression on mobile and workstation platforms:

- Providing an accurate performance and energy efficiency evaluation of modern compression and decompression utilities on three platforms that represent three distinct types of today's computer hardware: mobile devices, low-end devices, and workstations and servers.
- Evaluating the effects of frequency scaling on performance and energy-efficiency across all compression levels.
- Creating experimental environment for measurement-based energy profiling of the program running on mobile computing platforms.
- Creating experimental methods for energy profiling of programs running on a workstation and server computers.

1.5 Thesis Outline

The rest of thesis is organized as follows. Chapter 2 gives background on this research, including compression algorithms and utilities, mobile platforms, and power profiling. Chapter 3 presents related work by highlighting relevant studies performed in similar conditions. Chapter 4 specifies the experimental goals, metrics, datasets, measurement setup, and experiments conducted. Chapters 5, 6 and 7 discuss the results for each selected computing device, Pandaboard, Raspberry Pi, and the workstation, respectively. Chapter 8 summarizes the thesis, draws conclusions for all three platforms together, and gives suggestions for future work in the area of this study.

CHAPTER 2

BACKGROUND

This chapter covers background on several aspects of this research. Section 2.1 gives details on selected lossless compression utilities and their algorithms to provide understanding on how selected lossless compression utilities work at the basic level. Section 2.2 discusses each of the three computer platforms selected for evaluation, highlighting both hardware and software specifications of each. Section 2.3 discuses operating systems selection on both mobile and workstation computers. Section 2.4 discusses related work in power profiling.

2.1 Lossless Compression Utilities

The use of lossless compression can be found in various software distributions systems of Linux distributions, and Apple and Android app stores. For example, two most popular software package formats used in number of different Linux distributions are .deb (used in Debian based distributions) and .rpm (used in Red Hat based distributions). Those two packages contain application data that is retrieved from software repositories, and their content can be optional compressed with gzip, bzip2, lzma and xz. For app stores used in iOS and Android devices, .ipa and .apk file extensions are used for distribution of applications. Both file extensions are based on zip file format with various other extensions, such as encryption, and system specific (iOS or Android) structure built on top.

Table 2.1 lists the six lossless compression utilities that have been studied along with the supported range of compression levels and some commenting notes. The relatively fast gzip utility and the slower, but better compressing bzip2 utility were selected because of their widespread use in the Linux community. The lzop utility is included because of its exceptionally high speed. The xz utility is also gaining ground in the Linux community across different distributions and is known for its high compression ratio, slow compression, and fast decompression. Since some devices, including our Pandaboard, and the workstation computer are already equipped with multicore CPUs, pigz and pbzip2, which are parallel versions of gzip and bzip2, respectively, were included. All of these utilities operate at byte granularity and support a number of compression levels that allow the user to trade off speed for compression ratio. Lower levels favor speed, whereas higher levels result in better compression. Subsections below will cover each utility and algorithm in detail.

Table 2.1 Lossless Compression Utilities

Utility	Compression levels (default)	Version	Notes
gzip	1-9 (6)	1.4	DEFLATE (Ziv-Lempel, Huffman)
lzop	1-9 (3) (2-6 equivalent)	1.0.3	LZO (Lempel-Ziv-Oberhumer)
bzip2	1-9 (9)	1.0.6	RLE+BWT+MTF+RLE+Huffman (100KB-900KB)
xz	0-9 (6)	5.1.0alpha	LZMA2
pigz	1-9 (6)	1.1.5	parallel implementation of gzip
pbzip2	1-9 (9)	2.1.6	parallel implementation of bzip2

2.1.1 gzip

gzip [14] implements the deflate algorithm, which is a variant of the LZ77 algorithm [7]. It looks for repeating strings, i.e., sequences of bytes, within a 32 kB sliding window. The length of the string is limited to 256 bytes. gzip uses two Huffman trees, one to compress the distances in the sliding window and another to compress the lengths of the strings as well as the individual bytes that were not part of any matched sequence. The algorithm finds duplicated strings using a chained hash table that is indexed with 3-byte strings. The selected compression level determines the maximum length of the hash chains, and whether lazy evaluation should be used. The evaluated version of gzip is 1.4.

2.1.2 lzop

lzop [15] uses LZO block-based compression algorithm that favors speed over compression ratio and requires little memory to operate. It splits each block of data into sequences of matches (a sliding dictionary) and non-matching literals, which it then compresses. LZO requires no memory for decompression and requires only 64kB for compression. The speed for lzop is IO-bound and not CPU-bound. LZO algorithm provides support for a wide range of systems both legacy and new.

The lzop utility stores original file name, ownership, mode and time stamp of files during compression, allowing files to be restored in their original form when decompressed. Compression levels are divided into three groups. The first group includes compression levels -2, -3, -4, -5 and -6 and offers fast compression. The second group includes compression level -1 and it can be sometimes faster than the first group. The last group that includes compression levels -7, -8, and -9 provide the best compression ratio but with slower execution. Several standard switches are used to

turn on different options: *-f* forces compression or decompression, *-c* redirects output to a specified location, *-d* indicates decompression, and *–k* keeps the original file. No native parallel version of lzop currently exists, however process-level parallelism can be used when using GNU Parallel tool with lzop. The evaluated version of lzop is 1.0.3.

2.1.3 bzip2

bzip2 [16] implements a variant of the block-sorting algorithm described by Burrows and Wheeler (BWT) [8]. bzip2 applies a reversible transformation to a block of inputs, uses sorting to group bytes with similar contexts together, and then compresses them with a Huffman coder. The selected compression level adjusts the block size between 100 kB (with compression level -1) and 900 kB (with compression level -9). The evaluated version of bzip2 is 1.0.6.

2.1.4 xz

xz [17] is based on the Lempel-Ziv-Markov chain compression algorithm (LZMA) developed for 7-Zip [18]. It uses a large dictionary to achieve good compression ratios and employs a variant of LZ77 with special support for repeated match distances. The output is encoded with a range encoder, which uses a probability model for each bit (rather than whole bytes) to avoid mixing unrelated bits, i.e., to boost the compression ratio. The evaluated version of xz is v5.1.0alpha. For Pandaboard and Raspberry Pi, xz was evaluated only with compression levels -0 through -6 as the memory requirement for levels -7 to -9 exceeds the available memory on those platforms. For the workstation platform, this problem does not exist, and all compression levels of xz are evaluated.

2.1.5 pigz

pigz [19] is a parallel version of gzip for shared memory machines which is based on pthreads. It breaks the input up into 128 kB chunks and concurrently compresses multiple chunks. The compressed data are outputted in their original order. Decompression operates mostly sequentially, however separate threads are created for reading and writing [19]. The evaluated version of pigz is v1.1.5.

2.1.6 pbzip2

pbzip2 [20] is a multithreaded version of bzip2 that is based on pthreads. It works by compressing multiple blocks of data simultaneously. The resulting blocks are then concatenated to form the final compressed file, which is compatible with bzip2. Decompression is also parallelized. The evaluated version of pbzip2 is 2.1.6.

2.2 Evaluated Computer Platforms

For this research, three platforms with varying hardware complexity are selected so that the gained results and insights can have a wide application across many current mobile and workstation platforms. Pandaboard and Raspberry Pi are selected to represent typical mobile devices, and the workstation computer is selected to represent workstations and servers based on the state-of-the-art processors such as Sandy Bridge or Ivy Bridge [21].

2.2.1 Pandaboard

Pandaboard (Figure 2.1) is designed by Texas Instruments to support software development for smartphones and other mobile devices [22]. It features a Texas Instruments system-on-a-chip (SoC) OMAP4430 [23] with 1 GB of low-power DDR2 SDRAM. The OMAP4430 SoC includes a dual-core ARM Cortex-A9 MPCore processor, a 3D graphics accelerator, an image signal processor, and a rich set of

standard peripherals (timers, communication interfaces, and a memory controller). A number of commercial mobile devices, such as Amazon Kindle Fire, BlackBerry Playbook, Motorola Droid RAZR, Samsung Galaxy Tab and Galaxy S II, are based on this chipset. Pandaboard also features an onboard 10/100 Ethernet port, a wireless interface (802.11 and Bluetooth), DVI and HDMI video interfaces, an audio interface, and two USB ports.

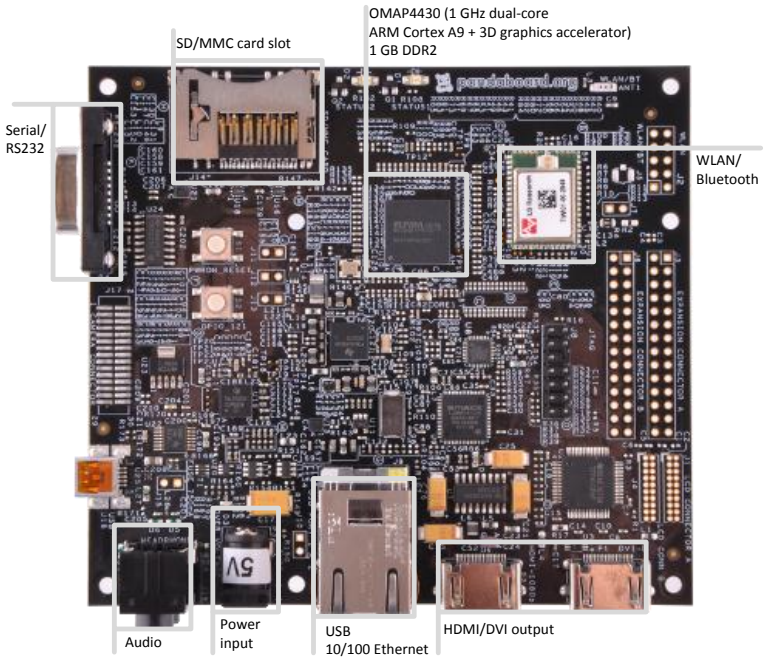


Figure 2.1 Pandaboard

The platform can run various mobile open-source operating systems based on the Linux kernel, including Ubuntu, Android, and MeeGo/Tizen. For experiments, Ubuntu distribution provided by Linaro, a non-profit organization that works on consolidating and optimizing open-source code for the ARM architecture [24], is se-

lected. Linaro provides both Android and Ubuntu for Pandaboard platform; however, the Ubuntu build is much more stable and provides more flexibility and control. One goal for performing highly representative measurements of compression or decompression on the selected platform was to have the ability to turn off any unrelated tasks in the system. With Linux, it was possible to kill all potentially results affecting tasks. This includes shutting down graphical desktop enlivenment, disabling network daemons when they are not in use (e.g, in experiments that do not involve network communication). Ubuntu and Linux are also gaining ground in the mobile systems. Canonical, a company that leads the development of Ubuntu announced their plans to enter the mobile market by demonstrating Ubuntu for phones, a standalone operating system for mobile devices. They plan to offer a full access to desktop operating system on smartphones, when they are docked with monitor and I/O devices. In addition, the Android, the most popular platform on smartphones relies on the Linux kernel.

2.2.2 Raspberry Pi

Raspberry Pi (Figure 2.2) is a credit-card size computer which is designed by Raspberry Pi Foundation to be readily affordable platforms for schools [25]. Raspberry Pi Model B was selected to represent low-end device for this research and features Broadcom BCM2835 SoC, which contains an ARM1176JZFS running at 700Mhz, a Videocore 4 GPU and 512MB of RAM. Model B also includes an onboard 10/100 Ethernet port, GPIO pins, RCA and HDMI video interface, an audio interface, two USB ports and SD card slot. Because no physical serial port is available on Raspberry Pi, the RX and TX pins on GPIO are used to setup a serial connection. Raspberry Pi has a large development community, which leads a number of projects

ranging from entertainment centers to dedicated computers for photography, home automation, medical and robotic fields. Raspberry Pi Foundation has sold close to a million devices [25] in less than a year since it has been introduced.

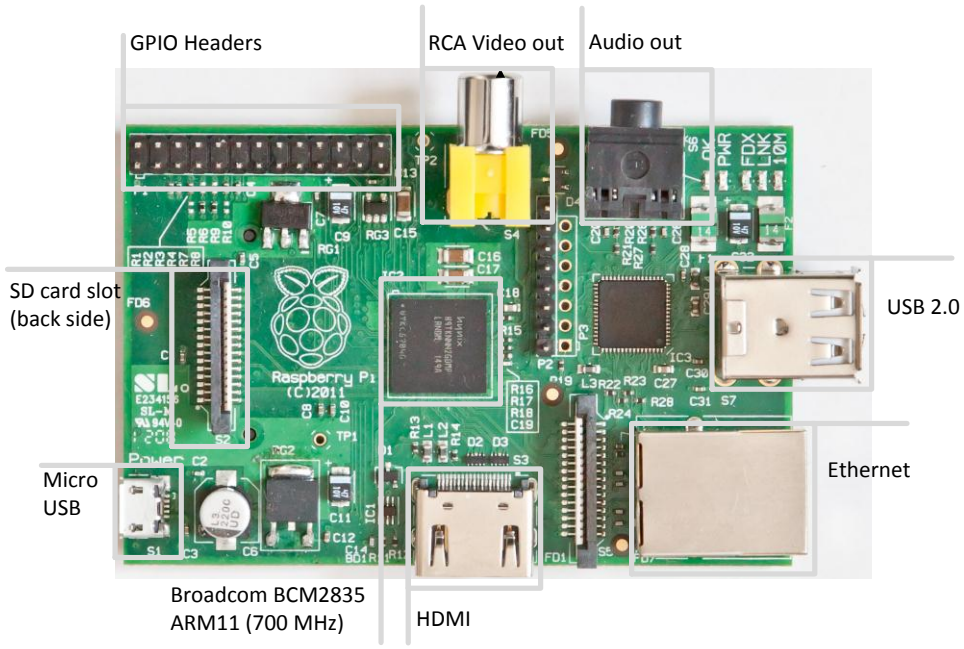


Figure 2.2 Raspberry Pi

Raspberry Pi supports several Linux distributions, including Debian [26], Arch [27] and several distributions built around XBMC (Xbox Media Center) such as Raspbmc and OpenELEC [28], [29]. Additionally, there are projects to provide support for Android operating system [30]. In this research, a Debian for Raspberry Pi is used.

2.2.3 Workstation platform

For the workstation platform, a Dell Precision T1600 workstation is used. It features a quad-core Intel Xeon CPU E31270 processor based on Sandy Bridge architecture. Each processor core supports 2-way multithreading; thus the total number of logical processor cores is eight. The processor chip supports ten frequency steps ranging from 1.60GHz to 3.40GHz. It features a three-level cache system, with 256KB L1 data cache, 1 MB L2 cache, and 8 MB L3 cache. The system memory is 8GB DIMM DDR3 synchronous at 1333MHz (0.8ns). The secondary storage includes an ATA hard disk with capacity of 1 TB. The workstation includes a gigabit network interface, a USB controller, audio and video interfaces, including NVIDIA Quadro GF106GL PCI Express graphics card.

The selected workstation allows the use of likwid lightweight performance tools to perform power measurement, specifically likwid-powermeter which will be discussed in details in Chapter 4. The Intel Xeon E31270 processor includes -- an on-chip resource for estimating energy and power of running tasks using events recorded in performance monitoring registers and their proprietary model that captures physical characteristics of the processor. The likwid tool interfaces the power meter and outputs power measurements in joules and watts. Intel researchers demonstrated that this on-chip resource gives estimates for the energy and power that are within several percentages of those acquired by the actual power measurements [21].

The workstation supports any operating system built to support i386 or x86_64 architecture. For this research, Ubuntu 12.04 was used to be consistent with experimental methods on other systems under test (Pandaboard and Raspberry Pi).

2.3 Operating Systems

This section gives a brief overview of operating systems for mobile and workstation platforms, and describes reasons for selecting Linux as the primary operating system for performing experiments across all selected systems in this research.

2.3.1 Mobile Systems

On mobile systems, two most popular operating systems are iOS from Apple, and Android from Google. Android and iOS capture 92% of the global smartphone shipments in Q4 of 2012 as reported by Strategy Analytics [31]. Similar market share is observed for both operating systems on tablets. The smaller market share is taken by Microsoft with their Windows Mobile and Windows 8 on smartphones and tablets. In addition to these three, there are other mobile operating systems that are either in development or command a much smaller market share. One example is Tizen [32], funded and developed by Linux Foundation, Samsung and Intel (a previous project MeeGo [33]). WebOS was converted by HP from a failed mobile attempt to an open source mobile project [34]. Firefox also recently started to develop a HTML5 based operating system with their Firefox OS [35]. Finally, Canonical, the group behind Ubuntu operating system, the most popular Linux distribution on desktops have introduced their mobile OS for mobile phones at Consumer Electronics Show (CES) of 2013 [36]. It is important to note that Ubuntu, in comparison with the majority of other mobile operating system, including iOS and Android, is offering the same operating system to be used across both mobile and computer devices, and proposing an idea of using powerful smartphone devices as full-desktop systems once they are docked to a special docking station connected to a monitor, keyboard, mouse and other I/O [37].

The majority of above mentioned operating system, excluding iOS and Windows Mobile or Windows 8, share a common feature of utilizing Linux kernel at their core. This indicates that anything that can work well on a basic level on Linux distribution (for example compression or decompression) will work well on the majority of mobile operating systems, including Android. This was one of the reasons why a Linux distribution (with the majority of unrelated tasks turned off) is selected to perform all measurement tests. This provided clean and reliable measurements and results that can be applied not only to Ubuntu, but easily to Android, Tizen, Firefox OS and other Linux based mobile operating systems. Another reason for using Linux, instead of Android, was better integration on development platforms and higher flexibility on controlling (turning off) running tasks.

2.3.2 Workstation and Server Systems

Linux is used on desktop, workstations and server systems across households, businesses and data centers. Linux is increasingly used in datacenters and server farms with w3tech reports that Linux is used in 32.8% of webservers [38]. Major companies such as Lenovo, Dell, IBM and HP are offering certified hardware [39] for various Linux distributions. New Linux-powered consumer products such as TV media centers [40] and gaming consoles [41] [42] are emerging. Those reasons were behind the choice of selecting Ubuntu Linux distribution as operating system for all performance and power measurement tests in this research. Similarly to mobile systems, Linux was also selected due to its higher flexibility and controllability.

2.4 Power Measurement and Profiling

This section discusses previous studies in the field of power measurement and profiling. Subsection 2.4.1 and Subsection 2.4.2 cover information for mobile and workstation systems, respectively.

2.4.1 Mobile Systems

There are a number of different studies that explore and seek for new ways of manage or reduce power consumption on mobile devices. This is motivated by limited battery operating time and consumers' demand for longer single charge mobile use. The proposed solutions on managing mobile power consumption include schemes with cloud offloading [43] [44], run-time power modeling [45] [46] [47], and energy estimation [48], [49].

Carroll and Heiser try to understand which component in today's typical mobile device are the biggest energy consumer by performing direct energy measurement [48]. They measured the energy consumed by individual components including CPU, RAM memory, flash storage, network and GPS. They evaluate different usage scenarios and applications such as audio playback, video playback, text messaging, phone calls, emailing and web browsing. The paper concluded that the majority of power consumption can be attributed to network communication and display. Their experimental setup, similar to the setup used in this thesis, consisted of using DAQ from National Instruments and a sense resistors inserted at the power supply rails to measure voltage drops across resistor, which is used for calculation of power and energy.

Bircher and John estimate system power consumption using processor performance events [49]. The complete list of performance events included cycles, halted

cycles, fetched micro-operations, L3 Cache misses, TLB misses, DMA accesses, processor memory bus transactions, un-cacheable accesses and interrupts. Analysis of performance events offline using software tools provided models and formulas for accurate power estimation for CPU, memory, disk and I/O. Accuracy of their method was demonstrated by synchronous comparison of estimations with direct hardware measurements. Downside to their study is the hardware dependent models and formulas, requiring adjustments and re-calibrations to provide proper power estimation for new systems.

2.4.2 Desktop, Workstation and Server Systems

Hardware modifications to support direct energy measurements are not always possible or desirable in mobile systems. This statement holds true for workstation and server computer systems, with some cases where hardware modifications can be almost impossible to perform. This subsection discusses the Intel's Sandy Bridge Power Control Unit (PCU) and how this on-chip power measurement infrastructure can be used to provide accurate power estimation without invasive hardware modifications.

Intel's Sandy Bridge allows for easier and more manageable ways for performing energy measurement and monitoring without doing invasive modifications to the hardware. Intel's PCU does not perform real energy measurements, but instead collects statistic on temperature and hardware events and then calculates power using proprietary models. Intel demonstrates remarkably low error of power estimation performed by the PCU when compared to direct hardware measurements on one such processor [21]. Subsections, in the experimental setup, will describe the software package, LIKWID [50], [51], [52], used to interface the PCU.

CHAPTER 3

RELATED WORK

This chapter covers the related work in the area of evaluation of lossless compression and decompression utilities on mobile (Sections 3.1) and workstation, and server systems (Section 3.2).

3.1 Mobile Systems

The most closely related work for wireless mobile devices in this research is a study by Barr and Asanović [10], [11], where evaluation of compression and decompression utilities is conducted with motivation of reducing wireless transmission energy cost.

Their excellent publications include details that are beyond the scope of this work, such as the frequency with which different types of instructions are executed, the branch prediction accuracy, and the performance of the memory hierarchy. Their experimental setup has several advantages. For example, their Skiff platform, which mimics an iPAQ mobile device, enabled them to separately measure the energy drawn by the CPU, the memory subsystem, peripherals, and the wireless interface. However, the test environment in this research is superior in other aspects. Some of them are simply a result of almost a decade of advances in technology. For instance, their now obsolete processor had a single core, a clock frequency of 233 MHz, and 32 MB of DRAM. The Skiff platform was further limited to 4 MB of nonvolatile flash memory. Thus, the root file system had to be mounted externally via an Ethernet port using NFS. In comparison, OMAP4430 has two cores, runs at 1.01 GHz and has 1 GB of DDR2 SDRAM. The OMAP SoC is one of the leading platforms for current

mobile devices and features an integrated communication interface and supports higher transmission speeds. Another advantage of our test bed is the use of DAQ which support sampling frequency up to 200kHz, which is about 5000 times higher than theirs, presumably yielding more accurate measurements. Even when 20kHz sample frequency is used, our hardware takes a sample every 50,000 and 35,000 CPU clock periods for Pandaboard and Raspberry Pi respectively, whereas theirs sampled once per five million clocks. In this research, variation of CPU frequency is also evaluated, providing insight into which frequency level can be more every efficient. There are also substantial software differences between Barr and Asanović's study and this research. Where-as several of their compression utilities are predecessors of the utilities evaluated in this thesis, they only tested a selected compression levels (while all compression levels are evaluated in this thesis), and inclusion of newer utilities such as xz as well as the parallel implementations pigz and pbzip2 is done. Furthermore, their input data was limited to 1 MB of text and 1 MB of web data. Data covered in this thesis is composed of a wider range of relevant data types with files size larger by an order of magnitude. Because of their hardware's low sampling rate, they were forced to run the same compression or decompression in an infinite loop to obtain sufficiently many samples. In this thesis however, individual test are run, that is, in a manner that is more representative of actual usage.

Study, by Xu et al., focuses only on decompression on mobile systems [12]. Their motivation to evaluation decompression tasks only laid in their assumption that performing compression on a mobile device is too costly in energy consumption. Their work compared gzip, bzip2 and compress. Similar to Barr and Asanović, they have used a similar iPAQ 3650 system to represent mobile device for their tests and their file server was Dell Dimension 4100 with 1GHz P-III processor. They establish

a wireless connection between iPAQ and file server using WaveLAN PCMCIA card which follows IEEE 802.11b standard. Their nominal peak rate was set 11Mb/s and their effective data rate of WaveLAN card was measured at 5Mb/s. For a portion of their work, they change nominal bit rate from 11Mb/s to 2Mb/s, however the rest of the work is done using 11Mb/s rate. To perform power measurement for their setup, authors use HP 3458a low-impedance digital multi-meter with sampling of several hundred samples per second. In comparison with work by Barr and Anasovic, Xu et al. have selected much wider array of test files used in their evaluation. Files varied heavily by individual file size and file type. Some of the selected file types, however, were already pre-compressed due to being either lossy or not suited for lossless compression (gif, jpg, mp3, m2v). The relevance to have such files under test is questionable as they produce compression ratios close to one. Otherwise, this study has many similarities with work of Barr and Asanović. Many observations on differences between Barr and Asanovic and work in this thesis can also be easily applied to paper by Xu et al. Differences include usage of all compression levels, substantially higher sampling frequency, due to a decade of advances in technology, new and parallel compression utilities, evaluation of frequency scaling and several software differences.

3.2 Workstations and Servers

Lossless file compression was considered for evaluation on the server and workstation computers by Kothiyal et al. [13]. In their work, they compare energy and performance results of some compression and decompression utilities for two platforms. A rack mountable sever Dell PowerEdge SC1425 with 2 dual-core Intel Xeon CPU @ 2.8GHz and a workstation system with Intel Pentium CPU @ 1.7GHz

were selected to represent a faster server dedicated system and slower common desktop system respectively. The main motivator of the study laid in power and cooling cost of data centers and server. Compression utilities gzip, lzop, bzip2 and compress, with selective compression levels were chosen for evaluation. However, even that evaluation included multicore system, no parallel compression utilities were selected for study. The Input set for compression tried to address the effect of compression ratio on performance and energy consumption by having four files, each with increasing compression complexity (each with lower compression ratio). For evaluation, only local compression with raw file transfer was considered, similarly to how network file transfer was used during network tests in this thesis. To better evaluate the activity in server class computers, authors came up with the read-write ratio model for their experiments. Using that model, they tested performance of compression utilities based on an increasing number of reads by having varied read-write ratio for each evaluation. The final report on energy consumption indicated that from all four compression utilities, under both systems, lzop -1 and -3 performed better than the rest, outperforming each raw file transfer for all read-write ratios and providing energy saving on all test stages. Final conclusion of the study was that energy-efficiency of any compression algorithm depends on how fast it executes.

CHAPTER 4

EXPERIMENTAL SETUP

Chapter 4 describes the experimental setup including goals, metrics, datasets, measurement setup, and types of experiments. Section 4.1 states experimental goals of this research. Section 4.2 covers metrics used for evaluation of compression ratio, performance, and energy efficiency. Section 4.3 covers two datasets that are selected. Section 4.4 describes measurement setup, breaking it down into separate discussions on Pandaboard/Raspberry Pi platforms and the workstation platform. Chapter is concluded by Section 4.5 with discussion on types of experiments selected for evaluation of compression and decompression utilities.

4.1 Experimental Goals

The experimental goals of this measurement-based research are to evaluate performance and energy efficiency of common compression and decompression utilities and to gain insights on selecting an optimal utility with minimal communication cost on mobile and workstation platforms. Experiments are performed in isolated and controlled environment to allow wide applicability of insights on other systems.

4.2 Metrics

Providing clear and easily applicable insights require well developed metrics for working with raw performance and energy data extracted from compression and decompression task. Metrics on evaluating compression ratio (Section 4.2.1), performance (Section 4.2.2), and energy efficiency (Section 4.2.3) are presented and discussed.

4.2.1 Compression Ratio

Compression ratio is used to evaluate the compression effectiveness of an individual utility on all levels of compression. The compression ratio CR is calculated as the size of the uncompressed input file (US) divided by the size of the compressed file (CS), CR=US/CS. Compression ratios, for each platform, are reported in Chapters 6, 7 and 8 that covers results for Pandaboard, Raspberry Pi and the workstation.

4.2.2 Performance

Performance of a compression or decompression task is inversely proportional to the time needed to complete the task. It depends on compression/decompression algorithms, file size, and redundancy found in the input files.

To evaluate the performance of individual compression utilities and their compression levels, the time to compress the raw input file (T.C) and the time to decompress (T.D) a compressed file generated by that utility with the selected compression level are measured using the Linux time utility that reports the elapsed time for a running task. Each compression or decompression task is repeated three times, and the average time is calculated. Instead of reporting the execution times directly, the compression and decompression throughput are reported, expressed in megabytes per second. They are calculated as the size of the uncompressed input file divided by the time to perform compression or decompression task (Equation (1)). Alternatively, the throughputs can be calculated as the number of bytes eliminated by compression, |US-CS|, divided by the time to perform compression or decompression task (Equation (2)).

$$Compression\ Throughput = \frac{US}{T.C}$$
$$Decompression\ Throughput = \frac{US}{T.D} \quad (1)$$

$$Compression\ Throughput\ Alt = \frac{|US - CS|}{T.C}$$
$$Decompression\ Throughput\ Alt = \frac{|US - CS|}{T.D} \quad (2)$$

The throughput from Equation (1) captures the efficiency of data transfers from a user point of view – users produce and consume raw data and care more about the time it takes to transfer data than about what approach is used internally to make the transfer fast. In addition, this metric is suitable for evaluating networked data transfers by comparing compressed and uncompressed transfers. Whereas the alternative throughput metric captures the compression strength of the individual utilities directly, it is not suitable for the evaluation of networked transfers.

4.2.3 Energy efficiency

For each compression task with a selected compression level, the energy overhead for compression (ET.C(0)) using the method described in Equation (3) is calculated. In addition, the total energy as a function of the idle current (ET.C(I_{idle}), I_{idle}={0.25, 0.5, 0.75} A) is derived. Similarly, for each decompression task the total energy as a function of the idle current ((ET.D(I_{idle})) is calculated. For each combination of a compression utility and a compression level, three measurements are conducted and the average energies are calculated. Instead of reporting the energy directly in joules, the energy efficiency calculated as the size of the uncompressed input file divided by the total energy to perform a compression or decompression task

is used. The energy efficiency calculations (measured in megabytes per joule) are given in Equation (3). Alternative energy efficiency metric can be calculated as the number of bytes eliminated by compression divided by the total energy (|US-CS|/ET.C or |US-CS|/ET.D) (Equation (4)).

$$\begin{aligned} Energy\ Efficiency\ \ for\ Compression &= \frac{US}{ET.C(I_{idle})} \\ Energy\ Efficiency\ \ for\ Decompression &= \frac{US}{ET.D(I_{idle})} \end{aligned} \tag{3}$$

$$\begin{aligned} Energy\ Efficiency\ \ for\ Compression &= \frac{|US-CS|}{ET.C(I_{idle})} \\ Energy\ Efficiency\ \ for\ Decompression &= \frac{|US-CS|}{ET.D(I_{idle})} \end{aligned} \tag{4}$$

4.3 Datasets

To perform effective evaluation of compression algorithms, proper datasets had to be compiled for each system under test. For this research, a total of two datasets are used. The first dataset, compiled specifically for mobile platforms, includes a set of diverse input files representative of mobile computing. The second dataset, selected specifically for the workstation platform, includes a 1GB image of Wikipedia.

The mobile input dataset file includes text, an executable, an image, a file with comma-separated values from a wearable health monitor, and source code. Table 4.1 describes the input files, including their types, size in bytes, and a short description. The files are merged into a single archive file (totalInput.tar) that is used as an input for the compression utilities.

Table 4.1 Dataset – totalInput.tar

i	Name	Type	Raw size [bytes]	Notes
1	book	text(txt)	15,711,660	Project Gutenberg Works of Mark Twain
2	libso	exec. (so)	12,452,484	An open source web content engine libwebkit library
3	globe	image (bmp)	16,777,270	An image of Earth from space
4	health	table (csv)	9,988,982	~2 hours of health and physical activity data collected on a portable health monitor
5	perl	code (tar)	11,233,280	Perl 5.8.5 source code

Specifically for the workstation platform, the second dataset is a dump of the English Wikipedia, "enwik9.xml" [53], composed of UTF-8 encoded XML which primary consist of English text from 243,426 article titles. A similar dataset, "enwik8.xml", is also known for being used in Hutter Prize for compression [54], [55]. Table 4.2 summarizes the two datasets used for this research, including their types, size in bytes, and a short description.

Table 4.2 Datasets Summary

i	Name	Type	Raw size [bytes]	Notes
1	totalInput.rar	Archive (tar)	66,478,080	Archived dataset from files in Table 4.1
2	enwik9.xml	web image (xml)	1,000,000,000	An image of Wikipedia consisting of English text

4.4 Measurement setup

Power and energy measurements for the mobile platforms rely on hardware instrumentation – a shunt resistor placed on the power supply rail is continually

sampled by a data acquisition system (DAQ). Power and energy measurements for the workstation platform rely on a software tool that interfaces the processor's on-chip power-measurement infrastructure, thus eliminating the need for hardware modifications [56]. The following subsections describe the measurement setup for the mobile platforms and the workstation platform.

4.4.1 Measurement Setup for Mobile Platforms

Figure 4.1 illustrates the setup for measuring energy consumed during a program execution on Pandaboard and Raspberry Pi. The only differences are that Pandaboard is supplied by a power brick with voltage and current outputs of 5V and 3.6A, whereas Raspberry Pi is supplied by a USB power adapter with voltage and current outputs of 5V and 2.0A. Both systems under test are connected to the power supply (V_{SUPPLY} = 5 V) via a low-resistance shunt resistor (R = 0.1Ω). The voltage over the shunt resistor (V_{SHUNT} = R*I) is sampled using a data acquisition (DAQ) system connected to a development workstation. The current I drawn by a platform can be calculated from the voltage drop over the shunt resistor as I = V_{SHUNT}/R.

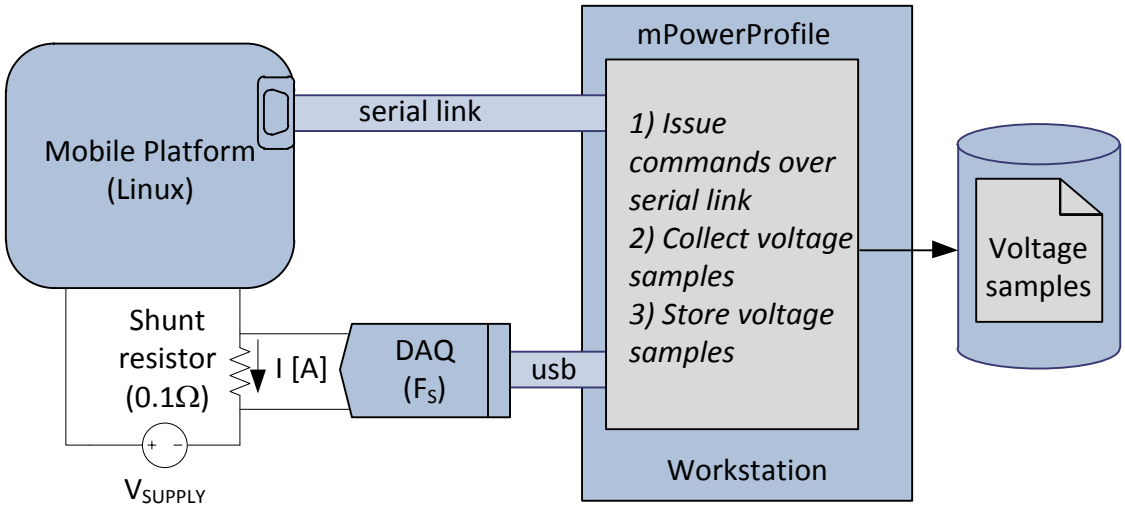


Figure 4.1 Measurement Setup for Pandaboard and Raspberry Pi

The development workstation (Dell Optiplex 745 with Windows XP) runs a custom mPowerProfile program that controls both system under test (via a serial link terminal) and the DAQ (via a USB port). mPowerProfile starts collecting voltage samples and, after a predefined head delay, a Linux command is issued to Pandaboard or Raspberry Pi. It collects samples during application execution as well as for a predefined tail delay after the application has completed. mPowerProfile provides utilities for configuring the head and tail delays, the scaling factor for samples, and the sampling frequency as shown in Figure 4.2. mPowerProfile allows for measurements on several channels at the same time.

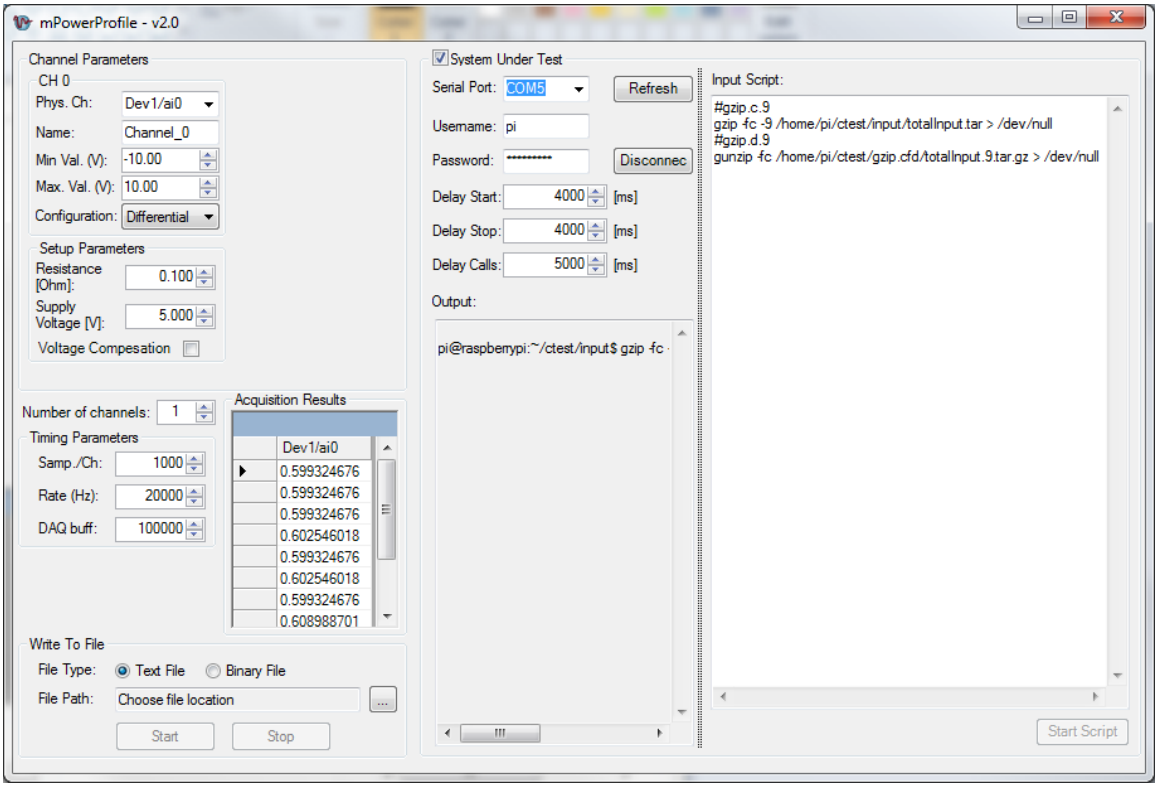


Figure 4.2 mPowerProfile software

The accuracy of the energy estimation increases with the increasing sampling frequency. The DAQ that used for this research is NI DAQPad-6015. It provides support for 16-inputs, with each having maximum sampling frequency of 200,000 samples per second (200 kS/s). DAQ also provides an API that mPowerProfile is using to control when and for how long to issue commands when performing measurements. Using the highest possible sampling frequency for DAQ on Pandaboard and Raspberry Pi, means that voltage can be sampled every 5,000 and 3,500 CPU clock cycles respectively.

When evaluating different sampling frequencies in the range of 10 kS/s to 200 kS/s, the result showed that the energy calculated using 20 kS/s is within 1% of

the energy calculated using 200 kS/s for both systems. Thus, for all experiments a sampling frequency of 20 kS/s is used. Using lower sampling frequency reduces the sizes of individual sample files substantially and allows for quicker processing of results without large sacrifice of accuracy.

4.4.1.1 Energy Calculation Example

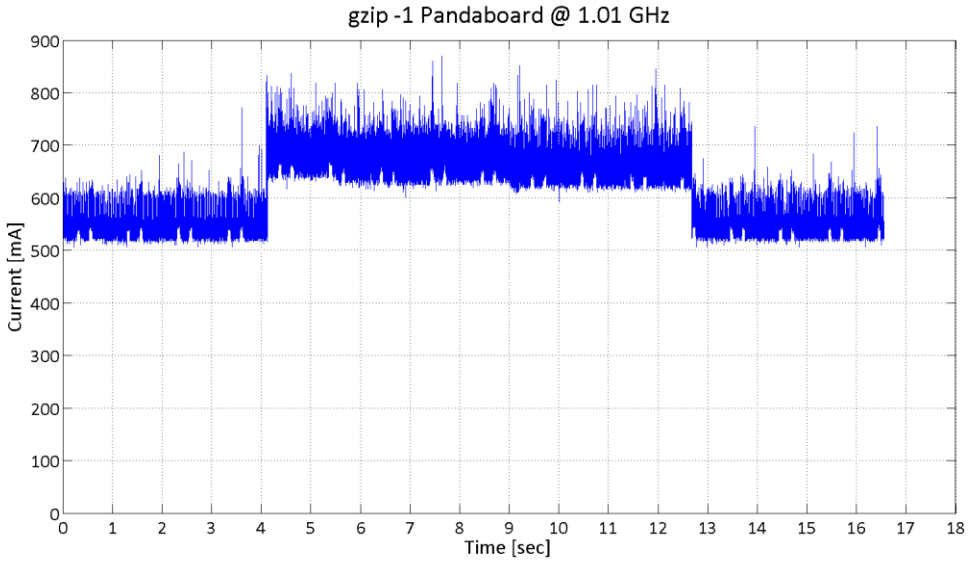
This subsection will demonstrate our methodology of performing energy measurement on Pandaboard or Raspberry Pi using mPowerProfile and Matlab (which is replaced later with Perl script to expedite the process).

mPowerProfile controls issuing commands to be run on the system under test and sampling voltage from the shunt resistor over the DAQ. Once mPowerProfile is properly configured, commands to be run on the platform are entered into Input Script window. By pressing "Start Script" mPowerProfile starts capturing samples from the shunt resistor into a specified file. After the predefined head delay, the command is sent to the platform through the serial COM port. Once the execution is done, mPowerProfile continues taking samples for the tail delay period. The collected samples are logged in the specified file as shown in Figure 4.3. Line 1 in the file contains configuration data of mPowerProfile and includes information such as Sampling Rate, Buffer size, Scaling factor, Start, Stop Delay and Date. Line 2 tells how many samples are recorded in the file. The remaining lines from Line 3 to the end of the file contain scaled voltage readings from the shunt resistor.

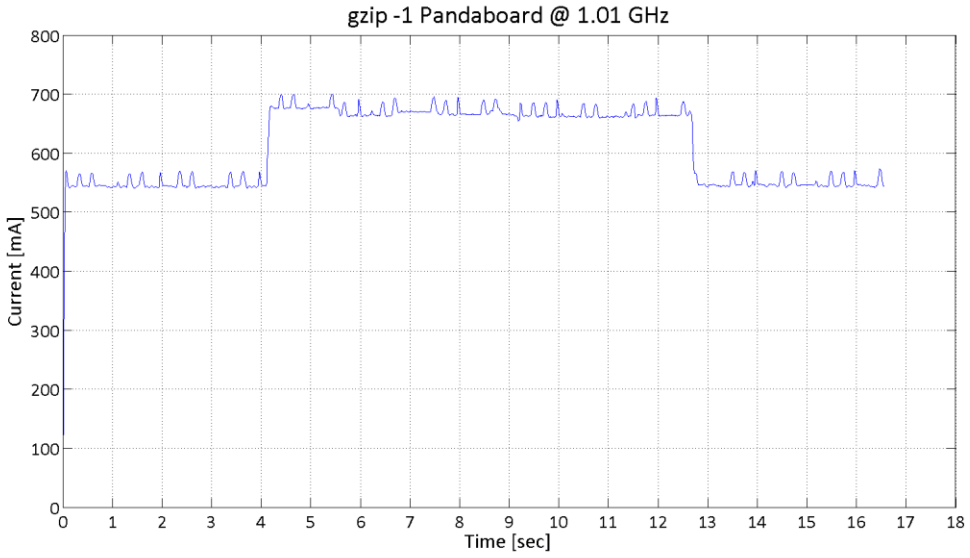
```
1. Sampling Rate = 20000, Buffer size = 1000, Scalling factor =
10000, Start Delay = 4000, Stop Delay = 4000, Date = 11/21/2011
5:30:19 PM
2. 1085000
3. 942.9931640625
4. 918.5791015625
5. 946.044921875
6. 952.1484375
7. 958.251953125
8. 942.9931640625
9. 961.3037109375
```

Figure 4.3 Sample File Example

Next step is to use Matlab, or Perl script to derive current and to calculate the energy. Figure 4.4 shows Matlab generated plots of the measured current drawn by Pandaboard during compression of the totalInput.tar input file using gzip -1. The head and tail delays are set in this example to 4 second each, and compression takes about 7 seconds. Figure 4.4(a) shows the current drawn by Pandaboard during this period as it is used in the energy calculations (raw samples from DAQ). Figure 4.4(b) shows the filtered signal, provided here only to enable easier visual inspection by a human of the changes in the current drawn during program execution.



(a)



(b)

Figure 4.4 Current drawn by Pandaboard during execution on gzip utility

Pandaboard with all unnecessary services turned off draws 0.565 amperes when idling (I_{idle} = 0.565 A) as shown in Figure 4.4. The start of compression is marked with a steep increase in the current, which remains high throughout the compression and goes down to the idle current once the application has completed.

The number of samples during the execution of a compression utility is n = T.C*SF, where T.C is the compression time for a given file and SF is the sampling frequency. The total energy consumed (ET.C) is calculated as follows:

$$ET.C = \sum_{j=1}^{n} I_j \cdot V_{PLATFORM,j} \cdot \Delta t \qquad (5)$$

where Δt=1/SF, and $V_{PLATFORM,J} = V_{SUPPLY} - I_J*R$. Note that the calculation can be simplified by assuming $V_{PLATFORM}$ to be constant because the voltage drop over the shunt resistor is negligible. In addition to ET.C, the energy overhead of the compression task, ET.C(0), is calculated alone which excludes the energy needed to run the platform when idle. This energy overhead is calculated as:

$$ET.C(0) = ET.C - I_{idle} \cdot V_{PLARTFORM,idle} \cdot T.C \qquad (6)$$

where $V_{PLATFORM,idle} = V_{SUPPLY} - I_{idle}*R$. Similarly, the total energy and the overhead energy for decompression tasks are calculated using the decompression time T.D instead of the compression time T.C. Once the energy overheads ET.C(0) and ET.D(0), are determined, total energies ET.C(I_{idle}) and ET.D(I_{idle}) as a function of the idle current using Equation (6) can be found and thus decoupling our findings from the system under test.

4.4.2 Workstation

A typical example of running likwid-powermeter on the workstation is shown in Figure 4.5. The first line creates a script file cmd.sh that performs a local compression task using gzip with -1. To get energy estimates, the likwid-powertool is run with the script file as a parameter. The likwid-powertool reports the conditions and the energy estimates (from line 03 to line 12). It shows the current clock frequency, the processor core id (CoreID 0) on which the task is run, the execution time,

and the energy consumed in Joules for the entire task (306.596 Joules) and the average power consumption (21.6 Watts).

```
01.~$ echo "gzip -fc -1 /dev/shm/input/enwik9.xml > /dev/null" >
cmd.sh
02.~$ likwid-powermeter ./cmd.sh
03.-------------------------------------------------------------
04.CPU name:       Intel Core SandyBridge processor
05.CPU clock:      3.39 GHz
06.-------------------------------------------------------------
07.Measure on CoreId 0
08../cmd.sh
09.Runtime: 14.1936 s
10.Domain: PKG
11.Energy consumed: 306.596 Joules
12.Power consumed: 21.6011 Watts
```

Figure 4.5 likwid-powermeter gzip -1 example

To conduct a systematic and an autonomous way of running tasks, a bash script is created which rewrite cmd.sh file, executes likwid-powermeter and parses output of likwid-powermeter for energy and time for each compression and decompression task repeatedly. The output of bash script produces two formatted text files, one with energy values and another with time of execution values for compression or decompression tasks.

4.5 Experiments

To evaluate compression and decompression tasks, three typical usage scenarios are considered as shown in Figure 4.7. This subsection describes the Local, Wired and Wireless experiments performed on selected systems under test, followed

by description of frequency scaling (Section 4.5.1) and idle currents (Section 4.5.2) and commands (Section 4.5.3).

The first experiment (Local) involves measuring the time and energy of compression and decompression tasks performed locally on the system under test. To eliminate latencies and energy overheads caused by reading and writing files from the file system on the SD memory card (for Pandaboard and Raspberry Pi) or the ATA disk (the workstation), the input files for the compression and decompression tasks are read from the tmpfs, a temporary Linux file system stored in main memory. The output of compression and decompression tasks is re-directed into the Linux null device (/dev/null) – a special "file" that discards all data written to it by calling write_null function that only increments the count with each incoming bit (Figure 4.6).

```
static ssize_t write_null(struct file *file, const char __user
*buf, size_t count, loff_t *ppos)
{
     return count;
}
```

Figure 4.6 write_null in Linux kernel source code for /dev/null

The second and third experiments (Wired and Wireless) involve measuring the time and energy of compression and decompression tasks performed on the system under test while communicating with a remote server. For the compression tasks, the raw input file (UF) is read from the local tmpfs, compressed on the platform, and streamed to the remote server over a secure channel. The output files are

redirected to the null device of the remote server. For the decompression tasks, the compressed files (CF) are retrieved from the temporary file system of the remote server through a secure channel and decompressed on system under test. The output files are redirected to the null device of system under test. The communication between input, compression/decompression, and output operations is carried out through Linux pipes. The execution times include file transfer latencies as well as compression and decompression times. Similarly, the energies are measured for completing the entire tasks. These two scenarios correspond to typical file-transfer tasks on selected platforms: compressing and uploading files to a remote server, and downloading files from a remote server and decompressing them. In addition to the transfers that involve compression and decompression operations, the time and energy needed to upload and download the raw input file over a secure communication channel were evaluated.

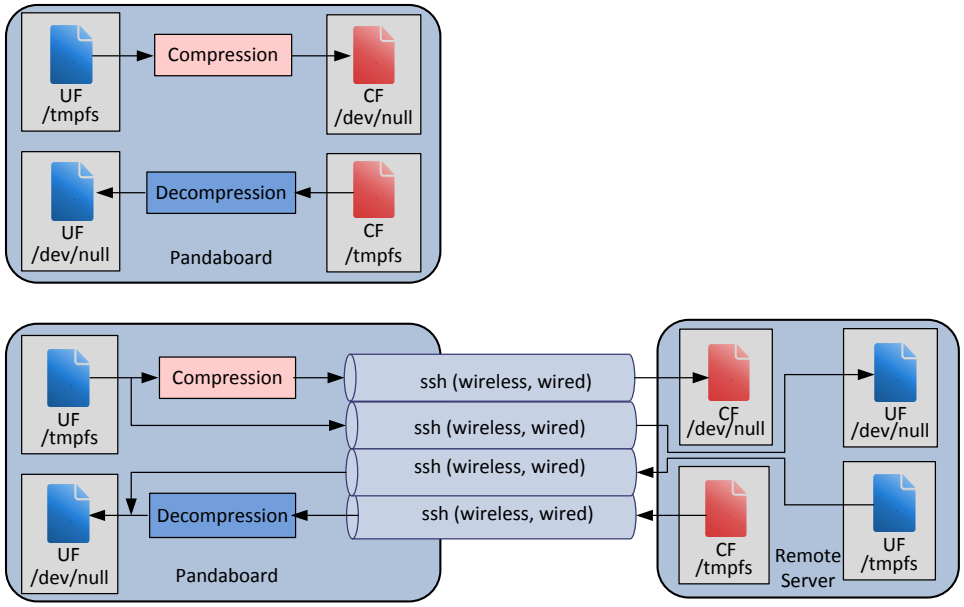


Figure 4.7 Experimental data flow

In the Wired experiment, system under test is connected to a local router using its Ethernet port. The remote server is also connected to the local router where no other nodes participate in any communication. In the Wireless experiment, system under test (Pandaboard) uses its wireless LAN interface (802.11n) to connect to the local router and through it to the remote server. The remote server for Pandaboard and Raspberry Pi evaluation was the same computer used for evaluation of the workstation system in this thesis, while remote server for the workstation evaluation was a similar workstation running Fedora distribution. The local router is a Linksys E900 Wireless N-300 with four 10/100 Ethernet ports.

Additionally, whereas Secure Shell (SSH) adds the extra task of data encryption/decryption, it reflects current practice and better represents realistic upload and download settings. Doing additional experiments to quantify the impact of the crypto operations in SSH on the transfer times and the energy consumed revealed that

their impact is not significant when compared to the netcat and wget utilities that do not use secure communication.

4.5.1 Frequency Scaling

To scale frequency in the mobile platforms or the workstation platform, cpufreq-utils from linux-tools is used in this thesis. This package provides two utilities, cpufreq-info and cpufreq-set. The cpufreq-info provides detailed information on the current state of the processor as shown in Figure 4.8. The cpufreq-set allows changing of the governor, or a policy rule for changing frequencies, maximum, minimum and current frequency steps.

```
cpufrequtils 007: cpufreq-info (C) Dominik Brodowski 2004-2009
Report errors and bugs to cpufreq@vger.kernel.org, please.
analyzing CPU 0:
  driver: acpi-cpufreq
  CPUs which run at the same hardware frequency: 0 1 2 3 4 5 6
7
  CPUs which need to have their frequency coordinated by soft-
ware: 0
  maximum transition latency: 10.0 us.
  hardware limits: 1.60 GHz - 3.40 GHz
  available frequency steps: 3.40 GHz, 3.40 GHz, 3.20 GHz, 3.00
GHz, 2.80 GHz, 2.60 GHz, 2.40 GHz, 2.20 GHz, 2.00 GHz, 1.80
GHz, 1.60 GHz
  available cpufreq governors: conservative, ondemand, us-
erspace, powersave, performance
  current policy: frequency should be within 1.60 GHz and 3.40
GHz.
                  The governor "ondemand" may decide which
speed to use
                  within this range.
  current CPU frequency is 1.60 GHz.
  cpufreq stats: 3.40 GHz:0.09%, 3.40 GHz:0.00%, 3.20
GHz:0.00%, 3.00 GHz:0.00%, 2.80 GHz:0.00%, 2.60 GHz:0.00%, 2.40
GHz:0.00%, 2.20 GHz:0.00%, 2.00 GHz:0.00%, 1.80 GHz:0.05%, 1.60
GHz:99.85%  (18646)
```

Figure 4.8 cpufreq-info output

4.5.2 Idle Currents

The isolated tests are ensured by disabling any unnecessary tasks or processes prior to conducting any experimental runs on both mobile platforms. This includes disconnecting unused hardware (leaving only serial and power cable connected), turning off GUI interface (leaving only terminal interface), and turning off network managers when no network is used.

For the Local experiment, Pandaboard has idle current of 0.51, 0.52, 0.54 and 0.55 mA for frequencies set to 300MHz, 600MHz, 900MHz and 1.01GHz respectively. For the Wired experiment, Pandaboard has idle current of 0.56, 0.57, 0.59 and 0.62mA for frequencies set to 300MHz, 600MHz, 900MHz and 1.01GHz respectively. For the Wireless experiment, Pandaboard has ide current of 0.52, 0.53, 0.54, 0.56mA for frequencies set to 300MHz, 600MHz, 900MHz and 1.01GHz respectively. For Raspberry Pi, idle currents for the Local and Wired tests are 0.36 and 0.42mA respectively for 700MHz frequency. Table 4.3 summaries all idle currents presented in this section.

Table 4.3 Idle Currents for Pandaboard and Raspberry Pi

Freq.	Local (mA)	Wired (mA)	Wireless (mA)	Notes
300MHz	0.51	0.56	0.52	Pandaboard 300MHz
600MHz	0.52	0.57	0.53	Pandaboard 600MHz
800MHz	0.54	0.59	0.54	Pandaboard 800MHz
1.01GHz	0.55	0.62	0.56	Pandaboard 1.01GHz
700MHz	0.36	0.42	-	Raspberry Pi 700MHz

4.5.3 Commands

To perform the evaluation of compression and decompression tasks on three experiments, several commands had to be generated. To perform time measurement of each running task, a time utility in Linux was using together with the compression or decompression command. To perform network communication, a SSH is used together with Linux pipes.

For the Local experiment, commands are shown in Figure 4.9 using an example with totalInput.tar dataset. Options –f and –c and -1 represent the force of compression or decompression, redirection of output and the selected compression level. For decompression, option for selecting compression levels is not necessary. Files p1_ctime_tar.txt and p2_ctime_tar.txt keep the output of the time command for each execution.

```
Compression:
(time gzip –fc1 /dev/shm/input/totalInput.tar > /dev/null) 2>>
/dev/shm/p1_ctime_tar.txt
Decompression:
(time gunzip –fc /dev/shm/gzip.cfd/totalInput.1.tar.gz >
/dev/null) 2>> /dev/shm/p1_ctime_tar.txt
```

Figure 4.9 Commands for the Local experiment

For the Wired and Wireless experiment, commands are shown in Figure 4.10. In addition to what was done for the Local commands, SSH and cat utilities are used together with Linux pipes to complete network transfers. Additionally, commands for raw transfer had to be generated for upload and download, to generate evalua-

tion data for the network transfer which is compared to compression and decompression tasks.

Compression:

```
(time gzip -fc1 /dev/shm/input/totalInput.tar | ssh ar-
mend@xeon-server "cat > /dev/null")
2>>/run/shm/p2_ctime_tar.txt
```

Decompression

```
(time ssh armend@xeon-server "cat
/dev/shm/gzip.cfd/totalInput.1.tar.gz" |gunzip -fc > /dev/null)
2>>/run/shm/p2_dtime_tar.txt
```

Upload

```
(time cat /run/shm/input/totalInput.tar | ssh armend@xeon-
server "cat
> /dev/null") 2>>/run/shm/p2_UC_ctime_tar.txt
```

Download

```
(time ssh armend@xeon-server "cat
/dev/shm/input/totalInput.tar" | cat > /dev/null)
2>>/run/shm/p2_UC_dtime_tar.tx
```

Figure 4.10 Commands for the Wired and Wireless experiments

CHAPTER 5

PANDABOARD RESULTS

This chapter presents the results of the experimental evaluation for the Pandaboard platform. Section 5.1 discusses the compression ratio achieved by the compression utilities for all supported compression levels. Section 5.2 discusses the compression and decompression throughputs. Section 5.3 discusses the energy efficiency of compression and decompression tasks. Section 5.4 discusses the effects of frequency scaling on processor cores. Section 5.5 summarizes findings from the Pandaboard experiments.

5.1 Compression Ratio

Figure 5.1 shows the compression ratio for the input dataset used with Pandaboard and Raspberry Pi platforms (totalInput.tar). pigz and pbzip2 achieve the same compression ratio as their sequential counterparts, gzip and bzip2, respectively. In general, the compression ratio increases with an increase in the compression level. However, a higher compression levels usually are computationally more complex, requiring more time and thus more energy. The best overall compression ratio is achieved by xz, ranging from 3.38 with -0 to 4.29 with -6; and by bzip2 (pbzip2) ranging from 3.49 with -1 to 3.91 with -9. The lowest compression ratio is achieved by lzop, ranging from 2.07 with -1 through -6 to 2.62 with -9. As described before, both Pandaboard and Raspberry Pi could not support xz with compression level 7 or higher due to high memory usage.

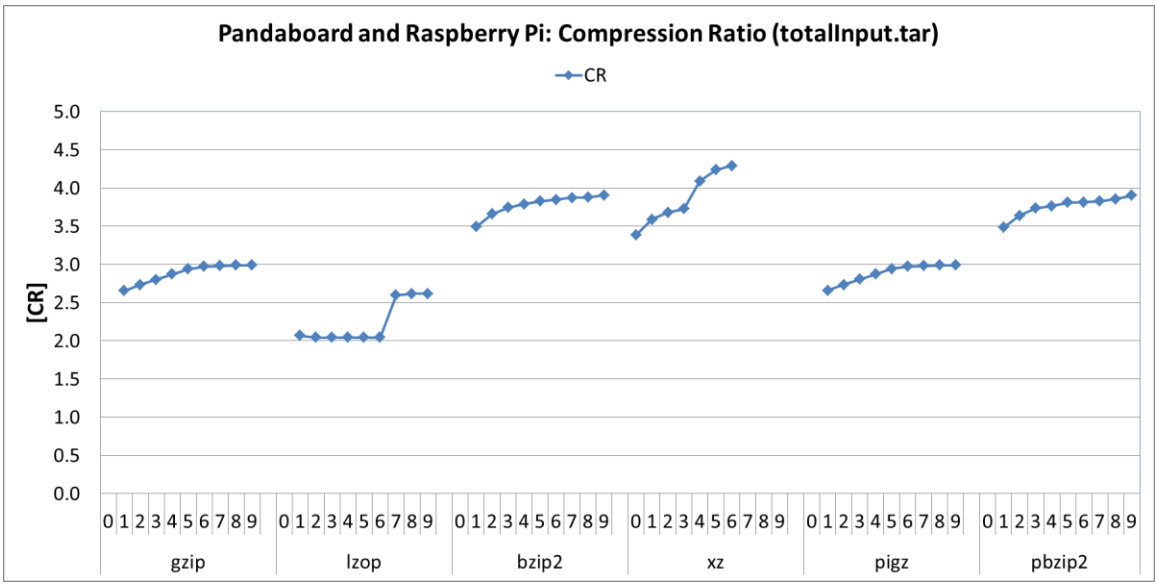


Figure 5.1 Pandaboard and Raspberry Pi: Compression Ration (totalInput.tar)

5.2 Compression and Decompression Throughputs

5.2.1 Local

Figure 5.2 shows the overall compression and decompression throughputs for the Local experiment expressed in MB/sec. The compression throughput varies widely across different compression utilities as well as across different compression levels of a single compression utility. For all compression utilities, the higher compression levels result in lower throughputs. By far the highest compression throughput of ~25 MB/sec is achieved by lzop -1 to -6. However, throughput of lzop drops dramatically to 1.37, 0.7, and 0.6 MB/sec for the highest compression levels (-7, -8 and -9 respectively). The second highest compression throughput from 13.2 to 2 MB/sec is achieved by pigz. It fully utilizes two processor cores to achieve close to double the compression throughput relative to gzip (from 7.4 to 1 MB/sec). In contrast, xz and bzip2 achieve significantly lower compression throughputs (e.g., from 1.6 to 1.1

MB/sec for bzip2). As with pigz and gzip, almost linear speedup in compression throughput is observed in pbzip2 relative to bzip2. xz slows down dramatically with increasing compression level to 0.28 MB/sec with -6, which is almost two orders of magnitude lower than lzop with -1.

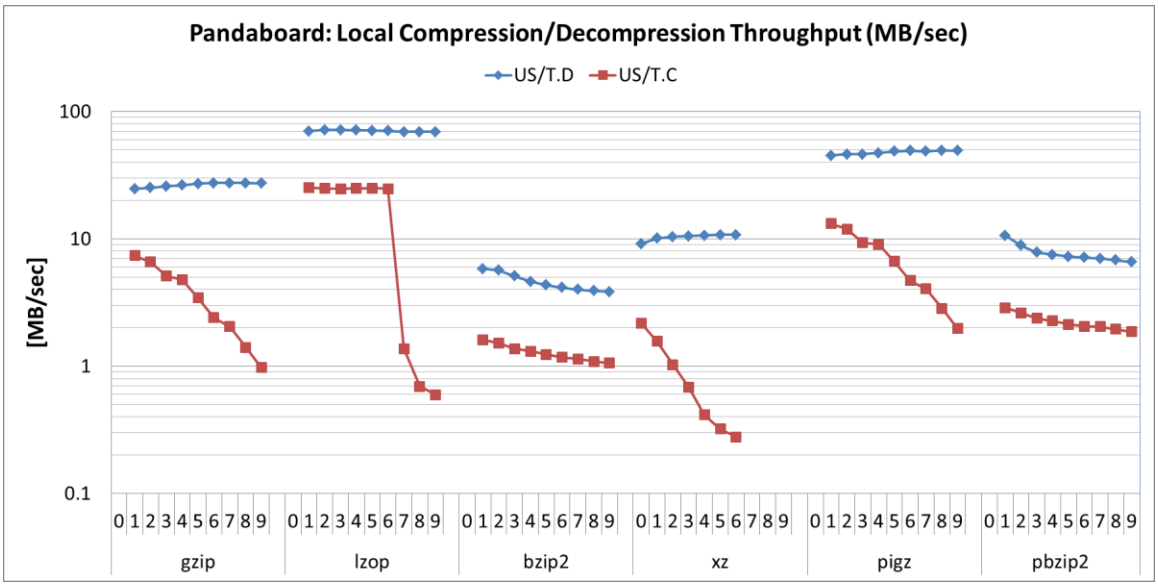


Figure 5.2 Pandaboard: Local Compression/Decompression Throughput

The decompression throughputs are much higher than the compression throughputs (from as low as ~3 times to over 112 times higher) and are only indirectly dependent on the compression level. The higher compression levels typically result in smaller compressed files, which may increase decompression throughputs because less time is needed to read the input files. Notable exceptions are bzip2 and pbzip2, where decompression throughputs slightly decrease for higher compression levels, in spite of smaller input files. This can be explained by the higher computa-

tional complexity of bzip2's decompression when input files are generated using higher compression levels. The highest decompression throughput of 71.9 MB/sec is achieved by lzop, followed by pigz (45.3 to 49.6 MB/sec) and gzip (24.7 to 27.5 MB/sec). xz achieves ~10 MB/sec, whereas pbzip2 ranges from 10.7 to 6.6 MB/sec and bzip2 from 5.8 to 3.8 MB/sec (both having lower decompression throughputs for higher compression levels). It should be noted that pigz and pbzip2 offer improvements in decompression throughputs over their sequential counterparts. Although decompression itself in pigz is not parallelized (it is single threaded), three other threads are created for reading, writing, and checking calculations that speed up decompression [19]. pbzip2's implementation includes parallelized decompression, thus fully benefiting from the dual-core processor in the OMAP4430 in Pandaboard.

5.2.2 Wired

Figure 5.3 shows the compression and decompression throughputs in the Wired experiment. The dashed lines represent the measured effective network throughput when the uncompressed input file is uploaded to the remote server (US/T.UUP = 5.95 MB/sec) and downloaded from the remote server (US/T.UDW = 8.84 MB/sec).

The compression throughput is limited by the effective network throughput and therefore it is always below the CR*(US/T.UUP). For example, lzop -1 (through -6) plateaus at 11 MB/sec, which is below 2.07*5.95 = 12.3 MB/sec (the compression ratio for lzop -1 is 2.07). The effective compression throughput in this case is thus significantly below the 25 MB/sec measured in the Local experiment. However, for lzop with -7, -8, and -9, where the original compression throughput is lower than the upload network throughput (5.95 MB/sec), the compression throughputs remain un-

changed relative to those measured in the Local experiment. Similar observations can be made about the other compression utilities. For gzip and pigz with -1, the compression throughputs are 6 and 8.3 MB/sec, respectively, well below the maximum achievable 15.8 MB/sec (2.65*5.95, where 2.65 is the compression ratio for gzip and pigz with -1). pigz with low compression levels offers only slightly higher compression throughput relative to gzip, but it almost doubles the throughput with high compression levels (e.g., 1.84 MB/sec vs. 0.95 MB/sec with -9). In contrast, pbzip2 consistently offers a higher compression throughput relative to bzip2 because they both have a compression throughput that is below the effective network upload throughput. When compared to the throughput for uploading the uncompressed dataset, only lzop with -1 to -6, gzip with -1, and pigz with -1 to -4 provide an increased effective network throughput, whereas the other combinations do not appear to be beneficial (i.e., it takes more time to compress and upload an input file than to just upload the raw input file).

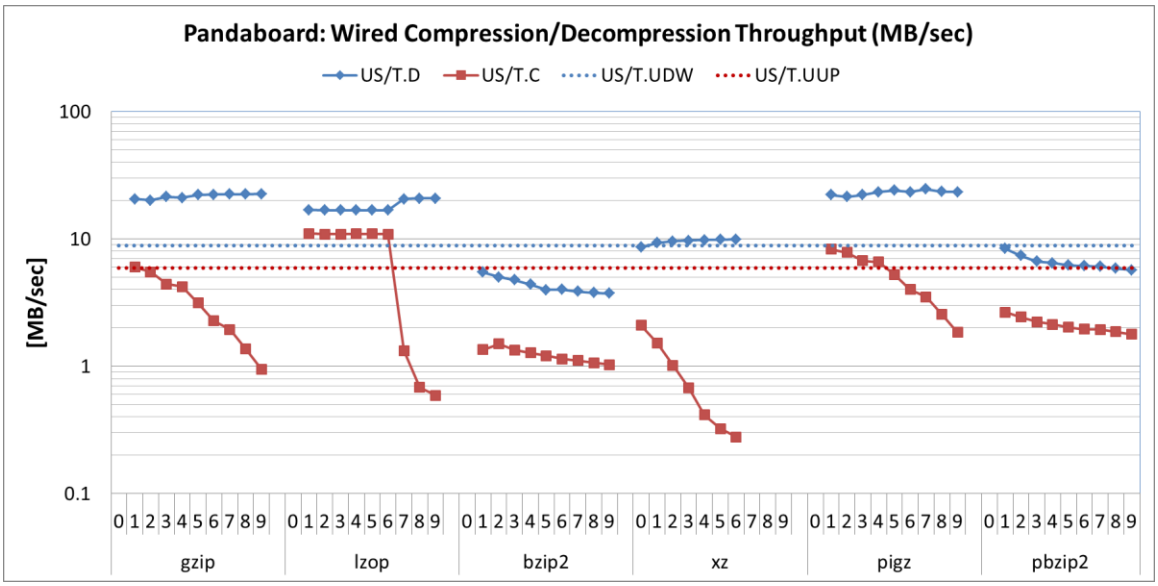


Figure 5.3 Pandaboard: Wired Compression/Decompression Throughput

The decompression throughputs are also limited by the effective network throughput, resulting in lower effective decompression throughputs, which are below CR*(US/T.UDW). For example, lzop with -9 achieves a decompression throughput of ~20.8 MB/sec, which is very close to the maximum achievable (2.62*8.84 = 23.2 MB/sec) but far below the 70 MB/sec measured in the Local experiment. gzip with -9 achieves ~22.6 MB/sec and pigz with -9 achieves ~23.5 MB/sec. They outperform lzop because they provide higher compression ratios – their achievable maximum decompression throughput is below 2.99*8.84 = 26.4 MB/sec. These three utilities effectively increase the available network throughput (their throughputs are above the US/T.UDW line) and decrease the download time relative to the time needed to download uncompressed files from the remote server. pbzip2 and bzip2 suffer from minor decreases in their effective decompression throughput relative to the Local experiment (due to the network latency) because their original decompression

throughput falls below the available network throughput for downloads (8.84 MB/sec). xz is on the boundary with its effective throughput ranging from 8.6 to 9.9 MB/sec (down from 9.1 to 10.8 MB/sec in the Local experiment).

5.2.3 Wireless

Figure 5.4 shows the compression and decompression throughputs for the Wireless experiment. The dashed lines represent the measured effective upload and download throughput when transferring the uncompressed file wirelessly, where US/T.UUP = 1.64 MB/sec (13.12 Mbits/sec) and US/T.UDW = 1.52 MB/sec (12.16 Mbits/sec), respectively. Similar to the prior experiments, the effective compression throughput is limited by the network upload throughput and is always below CR*(US/T.UUP). In the Wireless experiment, compression effectively increases the upload throughput for gzip with -1 to -7, lzop with -1 to -6, xz with -0, pigz with -1 to -9, and pbzip2 with -1 to -9, whereas bzip2 falls below 1.52 MB/sec. The lower effective network throughputs enable more compression configurations to be beneficial. Compression with lower compression levels is still preferred to higher levels. The highest compression throughput of ~5.1 MB/sec is achieved by pigz with -1. It outperforms gzip -1 (4.1 MB/sec) and lzop -1 (3.2 MB/sec).

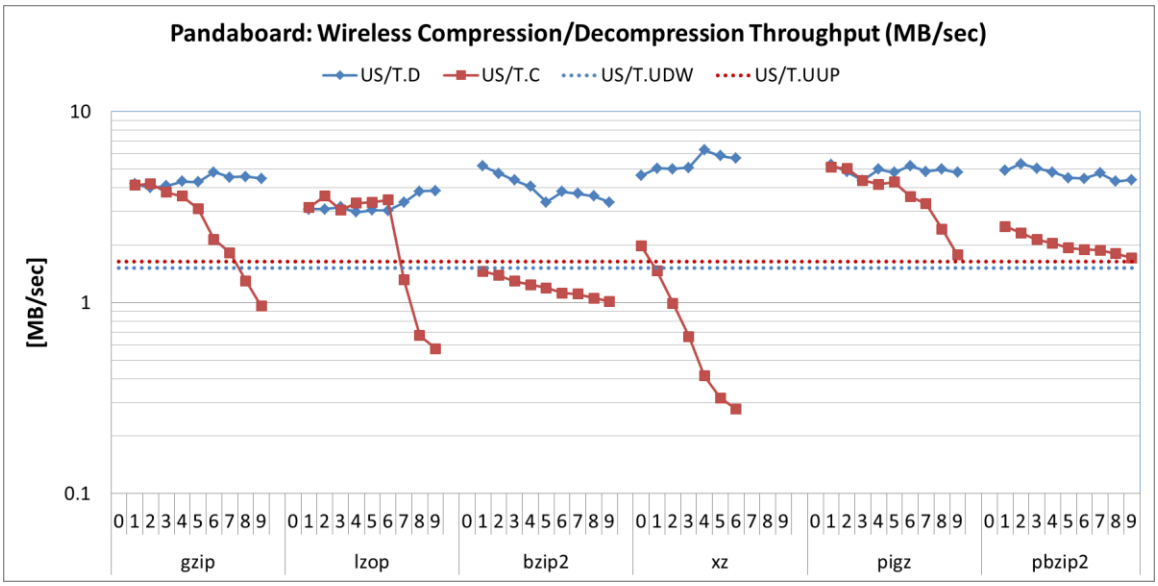


Figure 5.4 Pandaboard: Wireless Compression/Decompression Throughput

With the low effective throughput for downloads offered by the wireless interface, all compression utilities increase the available bandwidth (US/T.D > US/T.UDW) for all tested compression utilities with all compression levels. Again, the maximum achievable decompression throughput is limited to CR*(US/T.UDW). xz provides the highest decompression throughput, ranging from 4.6 with -0 to 6.3 MB/sec with -4, followed by pigz (from 4.3 to 5.3 MB/sec), and gzip (from ~ 4 to 4.8 MB/sec). The pigz and pbzip2 utilities offer only limited improvements in decompression throughput over their sequential counterparts due to CR* US/T.UDW limit.

In summary, the highest upload throughput, 5.1 MB/sec, is achieved by pigz -1; it outperforms over 3 times the raw file upload throughput (1.64 MB/sec). The highest download throughput, 6.3 MB/sec, is achieved by xz -4; it outperforms more than 4 times the raw file download throughput (1.52 MB/sec).

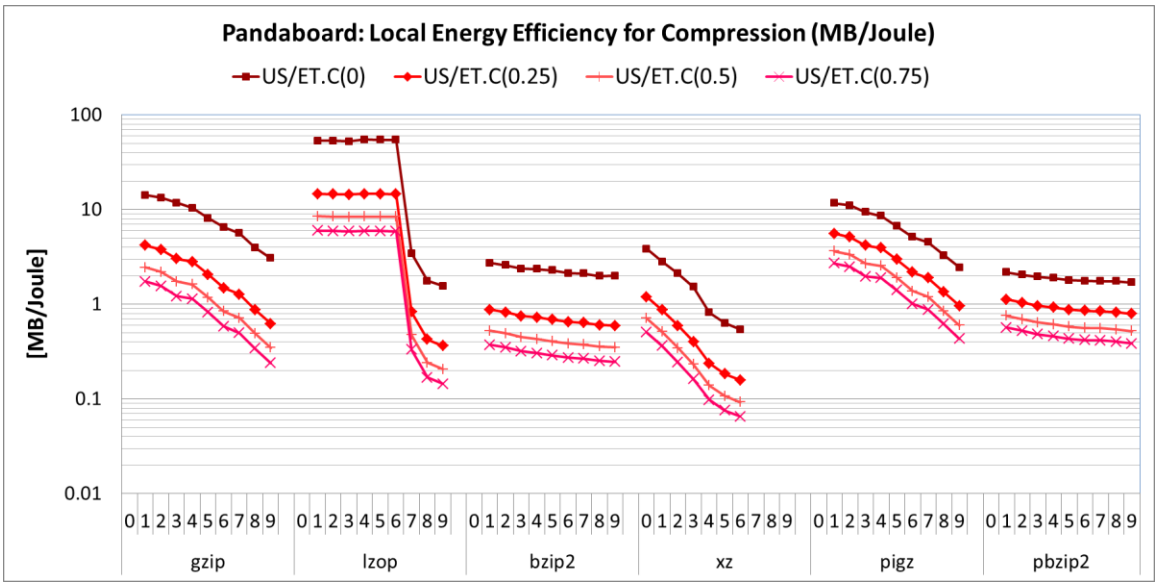
5.3 Energy Efficiency

5.3.1 Local

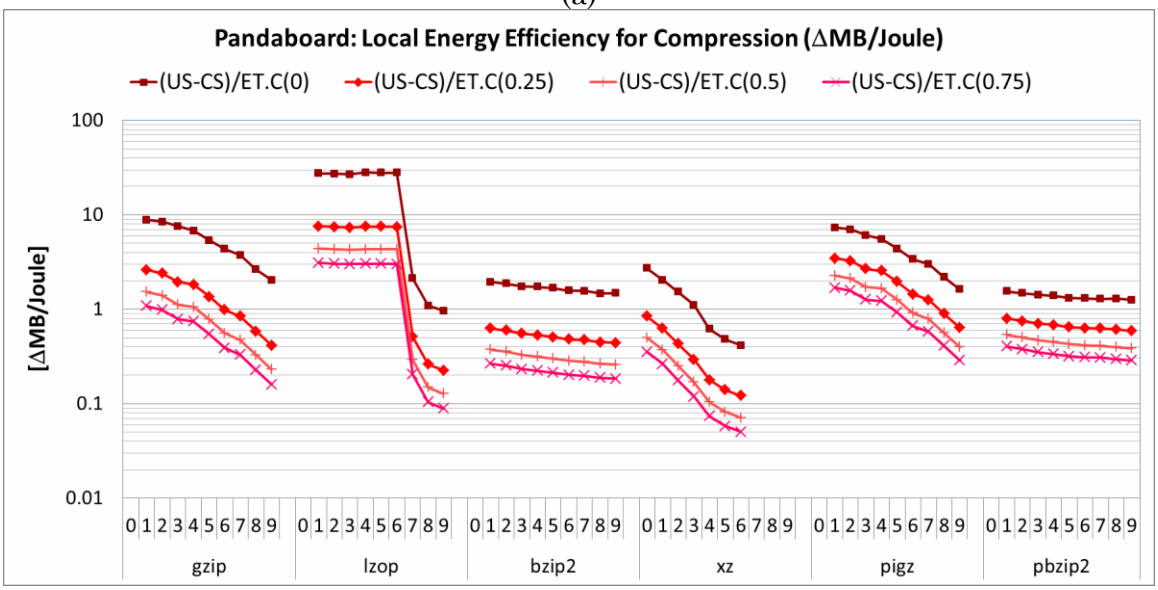
Figure 5.5 and Figure 5.6 show the energy efficiency for the compression and decompression tasks for the Local experiment reported in MB/J (US/ET.C and US/ET.D) and in ΔMB/J (|US-CS|/ET.C and |US-CS|/ET.D) as a function of the idle current I_{idle} (I_{idle} ={0, 0.25, 0.5, 0.75} A). In contrast to MB/J metric, ΔMB/J is a function of the amount of data removed by compression |US-CS|. Thus, this metric captures the strength of the compression utilities and compression level. To understand this better, |US-CS|/ET.C and |US-CS|/ET.D can be rewritten as (1-1/CR)*US/ET.C and (1-1/CR)*US/ET.D. The variable (1-1/CR) increases with increase in compression, thus all data points across both datasets for compression and decompression should be scaled by individual amount that depends on compression ratio. Knowing the lowest and the highest compression ratio in totalInput.tar dataset from Section 5.1, (1-1/CR) ranges from 0.52 to 0.76.

The energy efficiency of the compression tasks varies widely for different utilities and for different compression levels within each utility (often by more than an order of magnitude), as shown in Figure 5.5. The most energy efficient compression utility by far is lzop with compression levels -1 to -6 regardless of the idle current; it achieves ~54 MB/J (MB/joule) for I_{idle} = 0 A, ~14.5 MB/J for I_{idle} = 0.25 A, and 8.5 MB/J for I_{idle} = 0.5 A. Distant second and third are gzip and pigz with -1 achieving ~14 MB/J and ~11 MB/J for I_{idle} = 0. Following the trends in compression throughputs, higher compression levels for gzip, pigz, and lzop result in a dramatic decrease in energy efficiency (e.g., down to 1.5 MB/J for lzop with -9). pigz and pbizp2 are more energy efficient than their sequential counterparts when $I_{idle} \neq 0$ A

because they reduce the compression time. However, if we consider only the energy efficiency when I_{idle} = 0 A (US/ET.C(0)), the parallel implementations are slightly less energy efficient. pbzip2 and bzip2 exhibit low energy efficiencies as does xz, which is the least attractive choice with high compression levels. The alternative energy efficiency expressed in ΔMB/J follows similar trends as the regular energy efficiency.



(a)

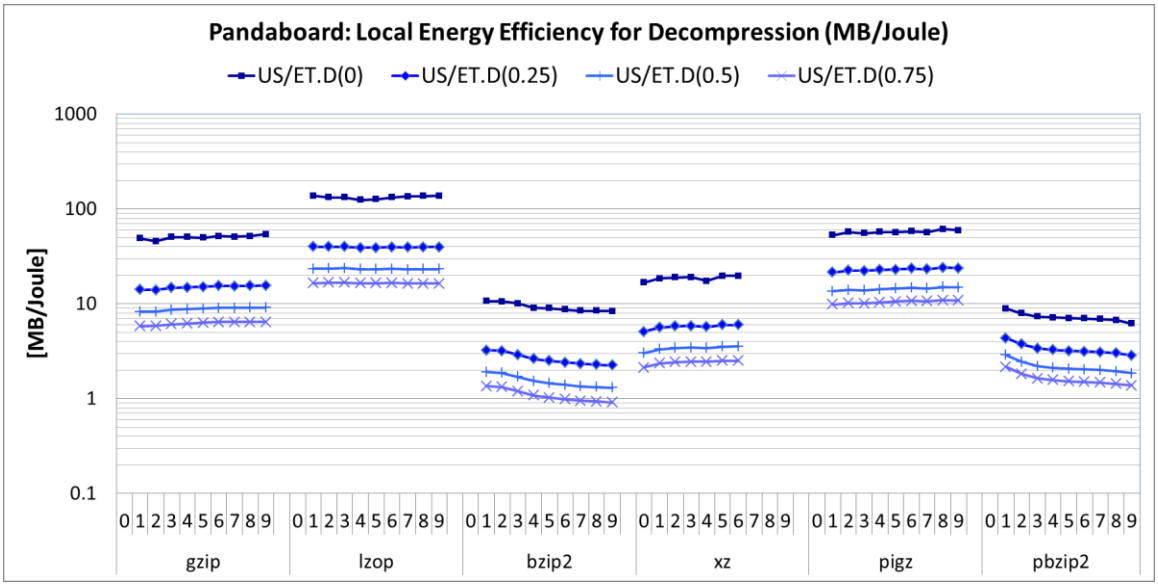


(b)

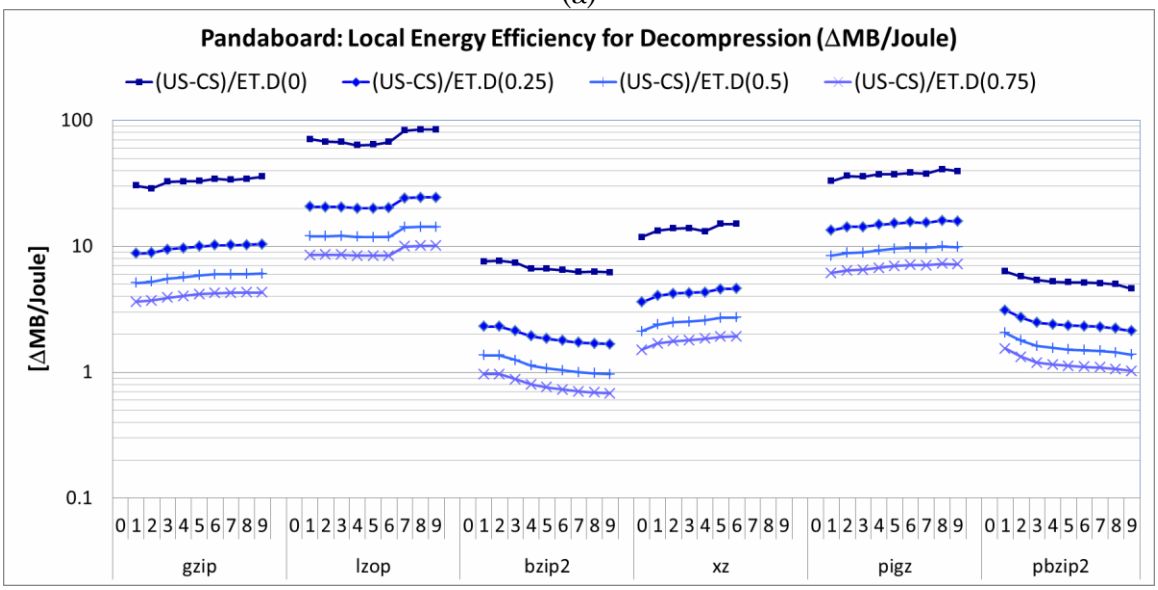
Figure 5.5 Pandaboard: Local Energy Efficiency for Compression

The energy efficiency of the decompression tasks varies widely for different utilities as shown in Figure 5.6. The energy efficiency is relatively stable for individual utilities – it increases slightly for higher compression levels for all utilities except bzip2 and pbizp2. Thus, US/ET.D(0) is ~136 MB/J for lzop, ~50 MB/J for gzip,

~55 for pigz, and just below ~10 MB/J for bzip2/pbzip2. lzop emerges as the most energy-efficient choice in spite of its lower compression ratio. These observation hold for the alternative definition of energy efficiency defined as (US-CS)/ET.D.



(a)



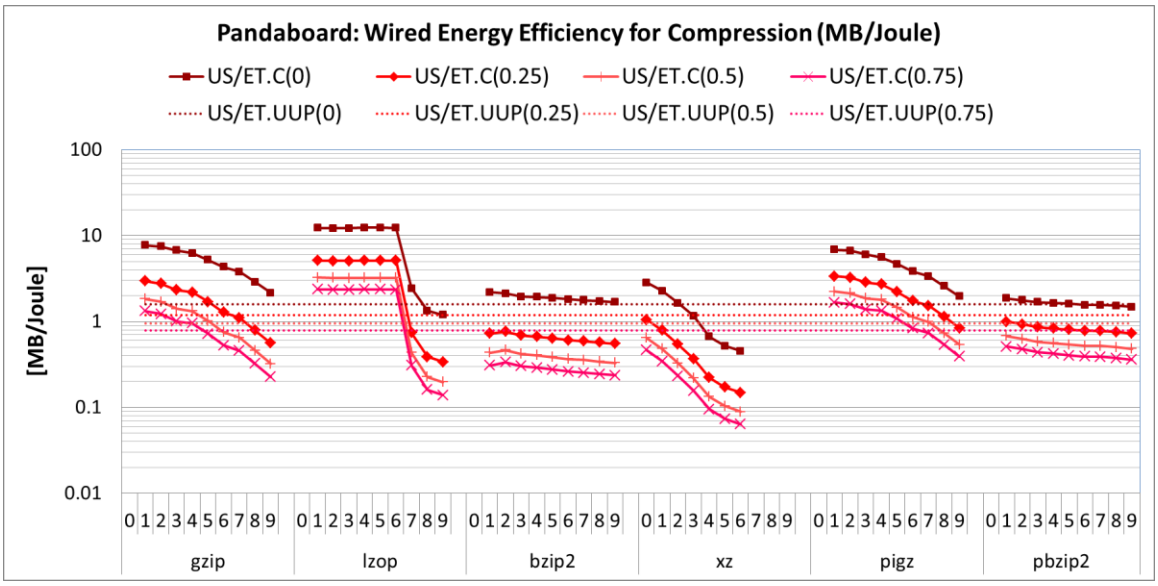
(b)

Figure 5.6 Pandaboard: Local Energy Efficiency for Decompression

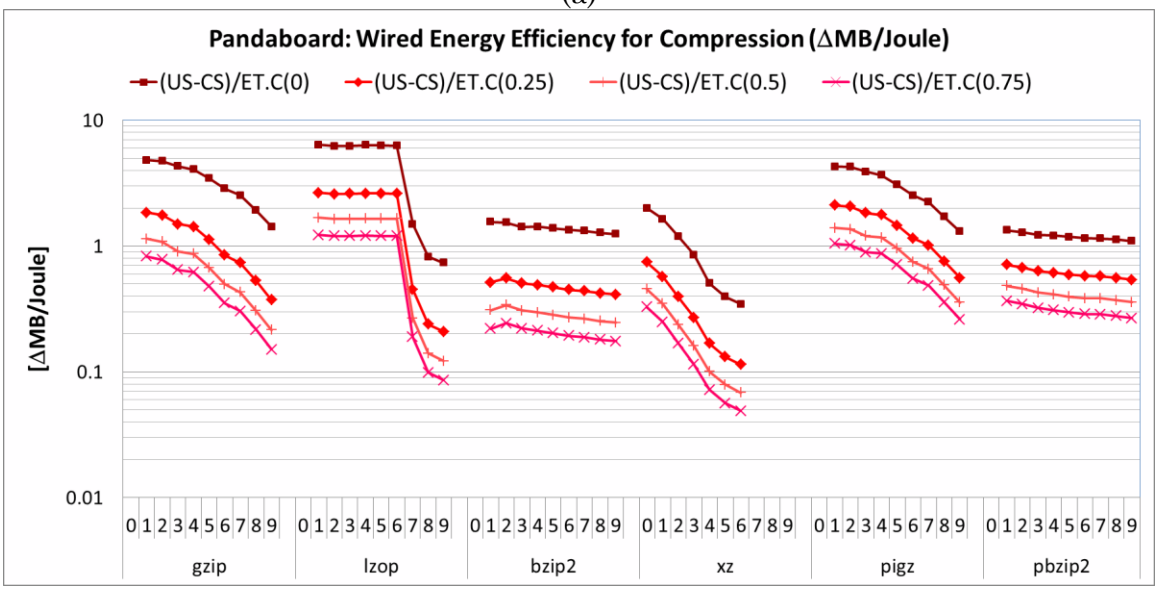
5.3.2 Wired

Figure 5.7 and Figure 5.8 show the energy efficiency for compression and decompression tasks for the Wired experiment reported in MB/J and in ΔMB/J as a function of the idle current. In addition, Figure 5.7(a) and Figure 5.8(a) show the energy efficiency for uncompressed upload (US/ET.UUP) and uncompressed download (US/ET.UDW) as a function of the idle current. This way, one can easily identify cases when compression and decompression transfers offer higher energy efficiency than raw uploads (US/ET.C(I_{idle}) > US/UUP(I_{idle})) and raw downloads (US/ET.D(I_{idle}) > US/ET.UDW(I_{idle})). With ΔMB/J metric, on other hand, energy efficiency for raw network transfer cannot be reported.

The energy efficiency for compression is reported in Figure 5.7. When I_{idle} = 0, gzip, pigz, and lzop with -1 to -7 and xz with -1 to -2 provide higher energy efficiency than the raw network upload. However, only lzop with -1 to -6, gzip -1 to -4, and pigz -1 to -5 provide higher energy efficiency for all considered idle currents. The most energy efficient utility is again lzop with -1 to -6 achieving ~12.5 MB/J when I_{idle} = 0, ~5MB/J when I_{idle} = 0.25 A, and ~3.25 MB/J when I_{idle} = 0.5 A. bzip2, pbizp2, and xz exhibit rather low energy efficiency for compression. These observations hold when the alternative energy efficiency metric is considered.



(a)

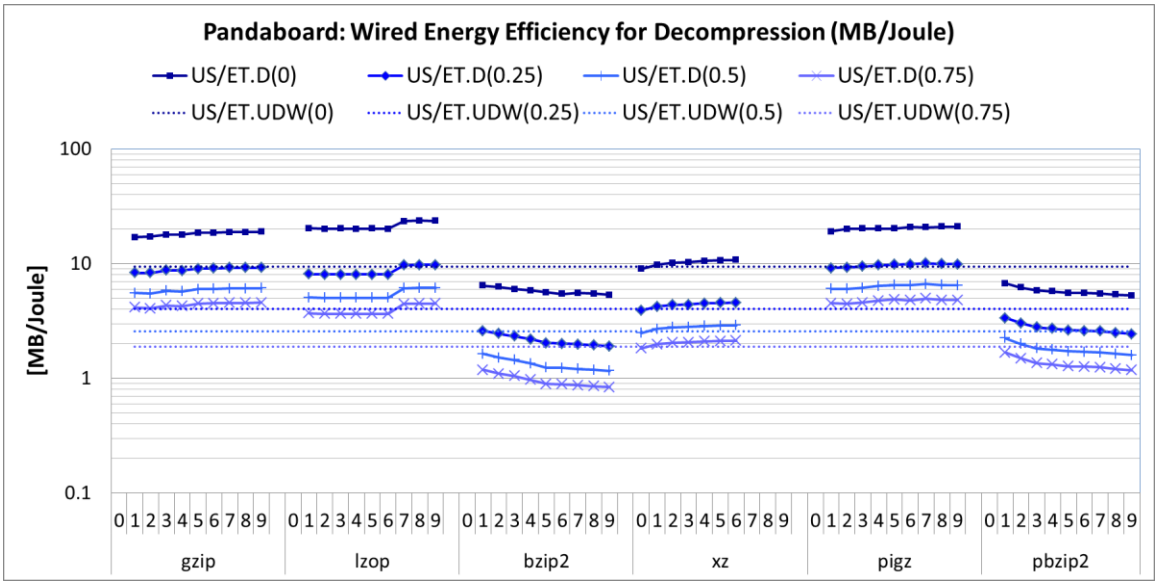


(b)

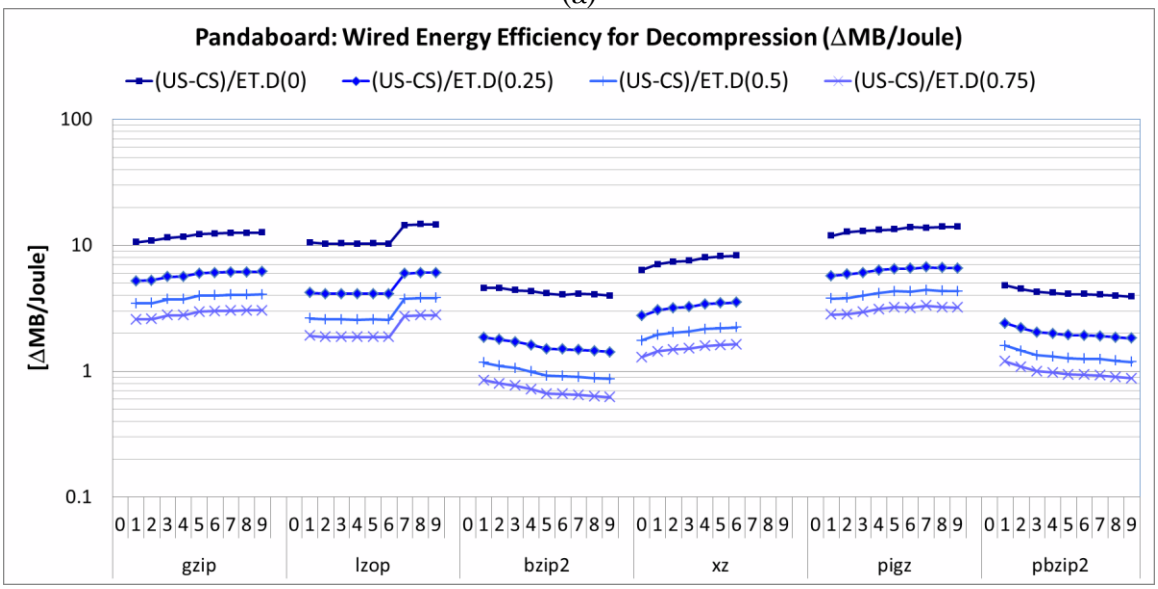
Figure 5.7 Pandaboard: Wired Energy Efficiency for Compression

The energy efficiency of the decompression tasks using gzip, lzop, and pigz exceeds the energy efficiency of the uncompressed download for all considered idle currents, whereas xz is only slightly beneficial, and bzip2 and pbzip2 are less energy efficient (Figure 5.8). The energy efficiency slightly increases for higher compression

levels (except for bzip2/pbzip2), achieving ~23.7 MB/J for lzop, ~ 21 MB/J for pigz, and ~19 MB/J for gzip when I_{idle} = 0 A. pigz emerges as the most energy-efficient utility, slightly outperforming gzip and lzop when I_{idle} = {0.25, 0.5, 0.75} A.



(a)



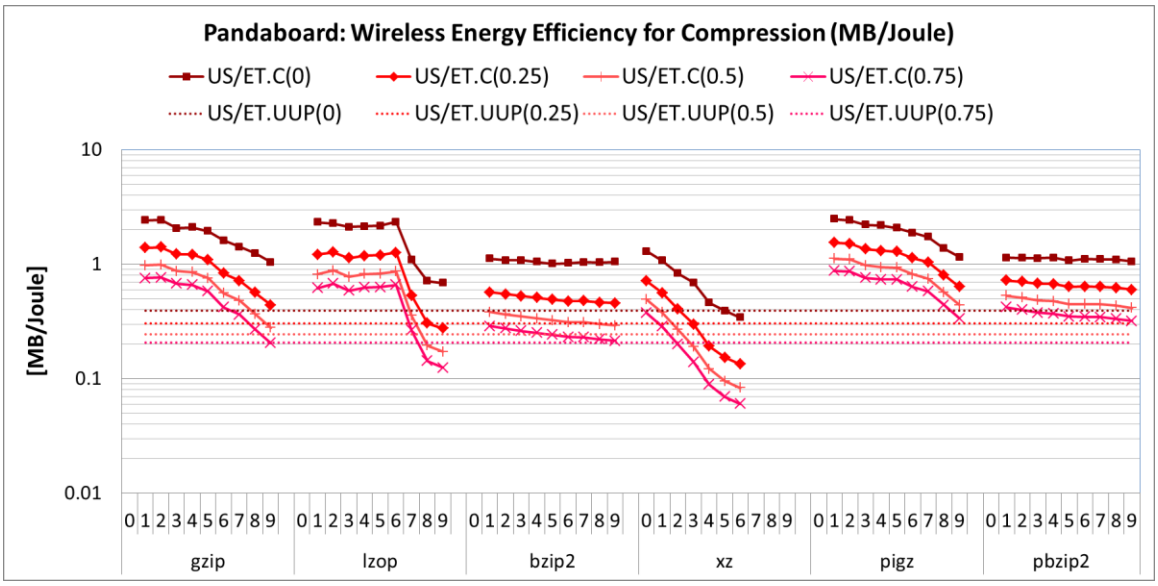
(b)

Figure 5.8 Pandaboard: Wired Energy Efficiency for Decompression

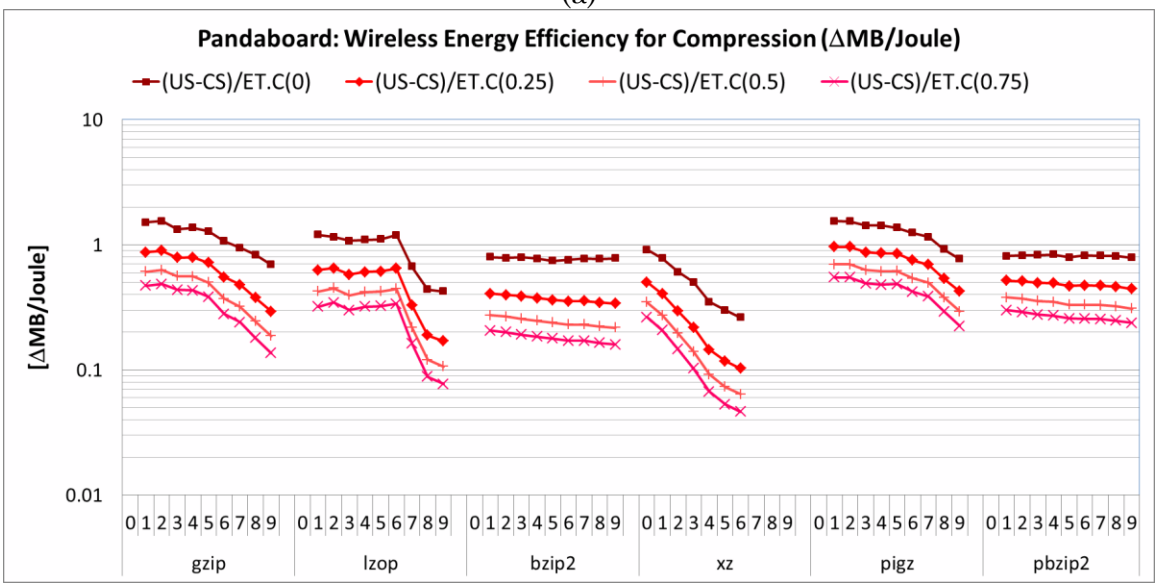
5.3.3 Wireless

Figure 5.9 and Figure 5.10 show the energy efficiency for the compression and decompression tasks for the Wireless experiment reported in MB/J and in ΔMB/J as a function of the idle current. Similar to the previous experiment, the graphs also display the energy efficiency for uncompressed upload (US/ET.UUP) and uncompressed download (US/ET.UDW) as a function of the idle current.

The energy efficiency for compression is reported in Figure 5.9. The relatively low network throughput for upload results in all utilities having higher energy efficiency than the raw upload when I_{idle} = 0 A (i.e., US/ET.C(0) > US/ET.UUP(0)) for all utilities except xz -5 and -6. pigz -1 is the most energy efficient with 2.5 MB/J, followed closely by gzip -1 and lzop -1. pigz -1 remains the most energy-efficient compression utility when I_{idle} = {0.25, 0.5, 0.75} A. For the ΔMB/J metric, the distribution of energy efficiency is the same for all utilities except lzop. lzop is lowered by a small degree in comparison with pigz and gzip.



(a)

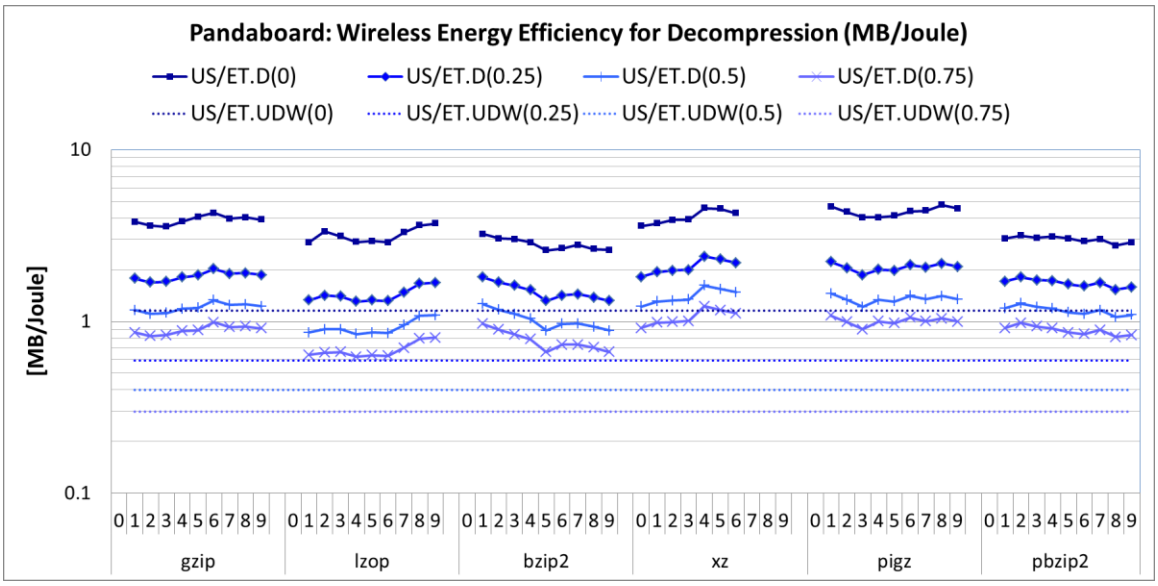


(b)

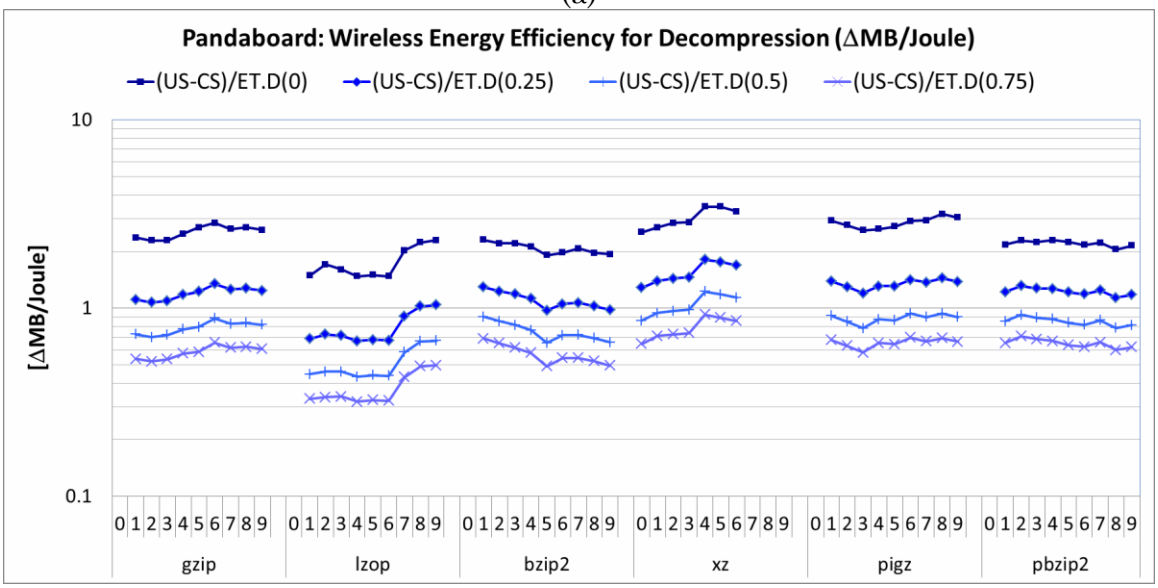
Figure 5.9 Pandaboard: Wireless Energy Efficiency for Compression

All decompression alternatives offer a total energy efficiency that exceeds the total energy efficiency of uncompressed download from the remote server, US/ET.UDW(0), which is 1.16 MB/J (Figure 5.10). Downloading files that were compressed with higher compression levels increase the energy efficiency except for

bzip2 and pbzip2. The total energy efficiency when I_{idle} = 0 A, US/ET.D(0), is ~3.6 - 4.3 MB/J for gzip, 2.9 - 3.7 MB/J for lzop, 4 - 4.8 MB/J for pigz, 2.9 - 3.1 MB/J for pbzip2, and 3.6 - 4.6 MB/J for xz. pigz and xz emerge as the most energy-efficient utilities when I_{idle} = {0.25, 0.5, 0.75} A. xz benefits from providing a superior compression ratio in conditions when communication energy dominates the overall energy costs.



(a)



(b)

Figure 5.10 Pandaboard: Wireless Energy Efficiency for Decompression

5.4 Frequency scaling

The frequency scaling for the Pandaboard platform covers frequency steps of 300MHz, 600MHz, 800MHz and 1.01GHz (with highest frequency used to describe the results from Section 5.2 and Section 5.3). To evaluate the effects of frequency

scaling, a complete set of tasks are repeated for each frequency step. The results on throughput and energy efficiency of compression and decompression tasks are discussed for the Local, Wired and Wireless experiments.

5.4.1 Local

5.4.1.1 Compression and Decompression Throughputs

Figure 5.11 and Figure 5.12 show the compression and decompression throughputs in the Local experiment. All utilities benefit from higher frequency.

For the compression tasks, the highest throughput across all frequencies is achieved by lzop -1, achieving 25.32 MB/sec on 1.01GHz and 8.20 MB/sec on 300MHz (Figure 5.11). Following lzop, pigz and gzip come in second for having higher throughput for all frequency levels when compared to other utilities.

For the decompression tasks, the highest throughput across all frequencies is achieved by lzop -1, achieving ~70 MB/sec on 1.01GHz and 22.32 MB/sec on 300MHz (Figure 5.12). Following lzop, pigz and gzip come in second for having higher throughput for all frequency levels when compared to other utilities.

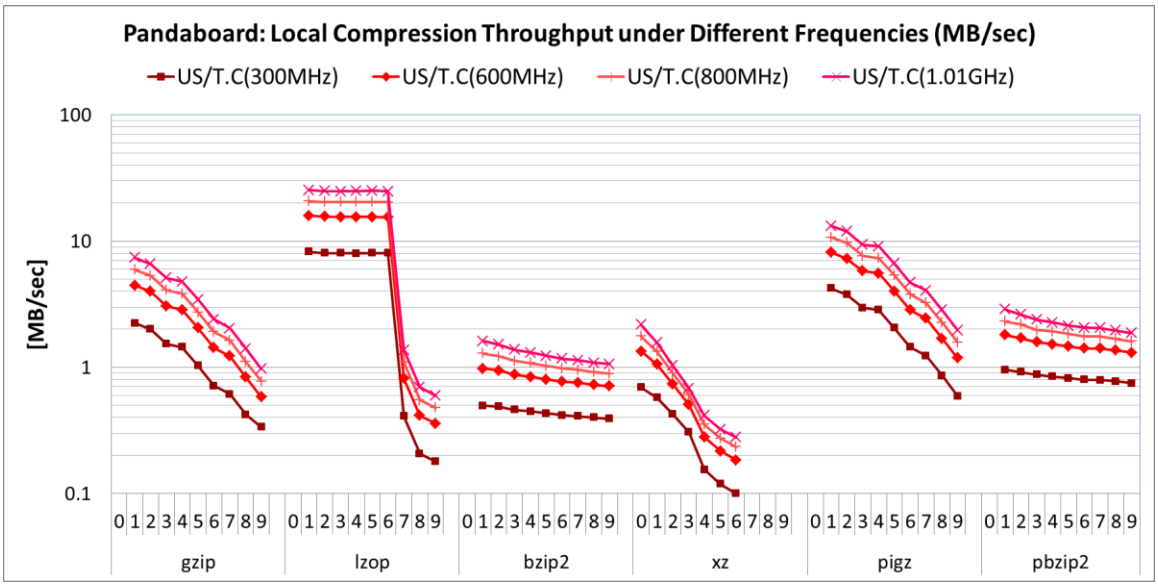


Figure 5.11 Pandaboard: Local Compression Throughput under Different Frequencies (MB/sec)

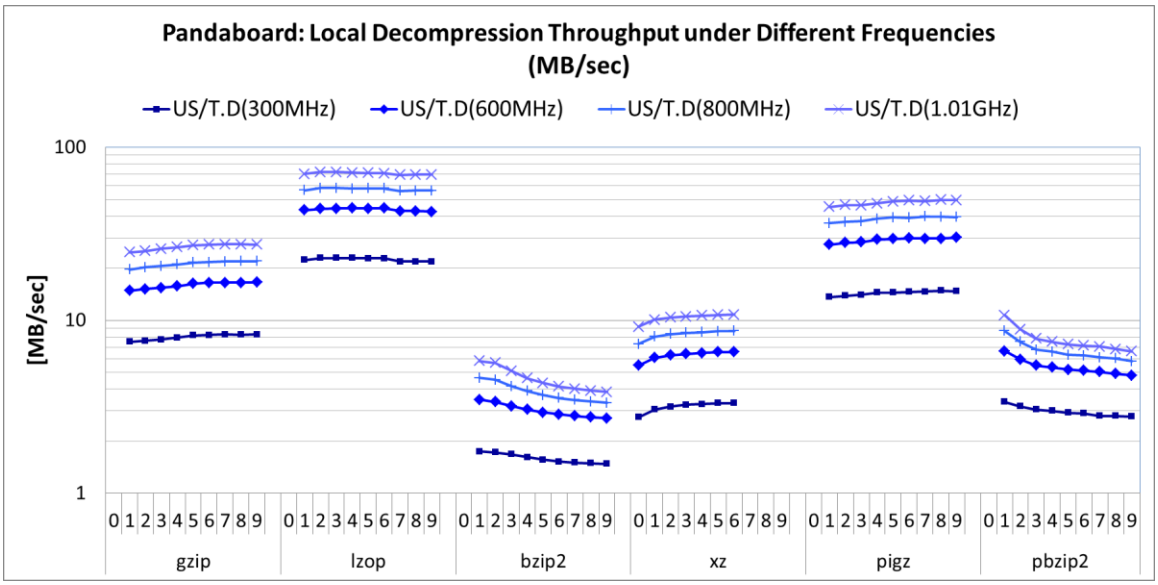


Figure 5.12 Pandaboard: Local Decompression Throughput under Different Frequencies (MB/sec)

Figure 5.13 shows comparison between throughput ratios and frequency ratios for the compression and decompression tasks in the Local experiment. The throughput ratio is derived by dividing the throughput achieved for highest frequency (1.01 GHz) by the throughput achieved for other frequencies (300MHz, 600MHz or 800MHz). This ratio is compared to the frequency ratio derived by dividing the highest frequency by the corresponding frequency (300MHz, 600MHz or 800MHz). The utilities such as gzip, lzop and pigz have almost identical throughput ratios as their corresponding frequency ratios, indicating linear relationship between frequency scaling and throughput change. Similar observation can be made for xz during decompression. The higher compression levels of bzip2 and pbzip2 have lower throughput ratios when compared with their frequencies ratios, indicating non-linear throughput change with frequency scaling on higher compression levels. The same observation can be made for higher compression levels of xz during compression.

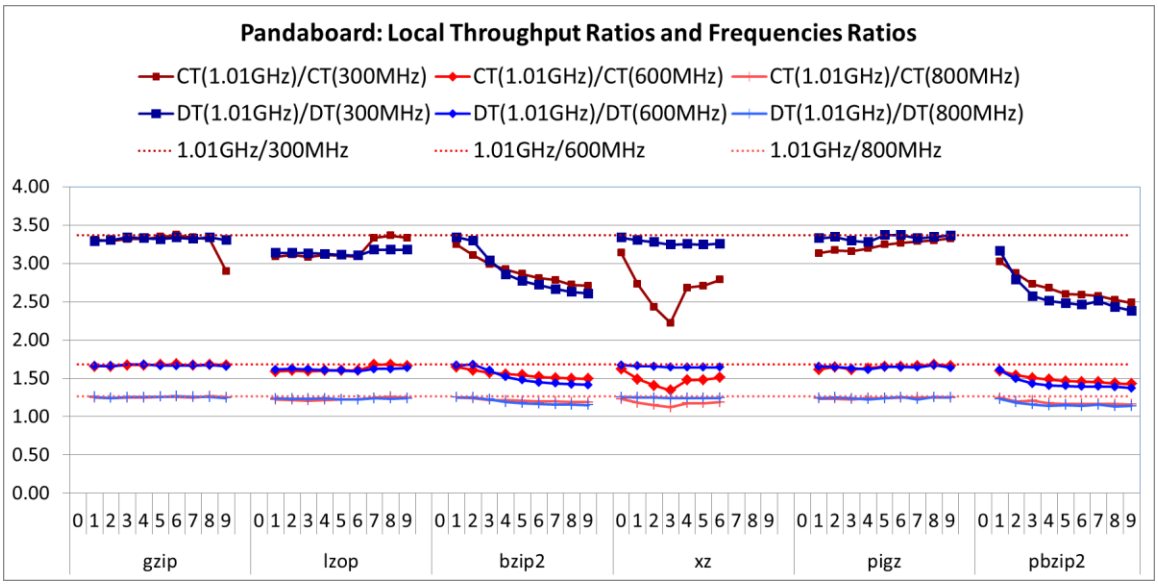


Figure 5.13 Pandaboard: Local Throughput Ratios and Frequency Ratios

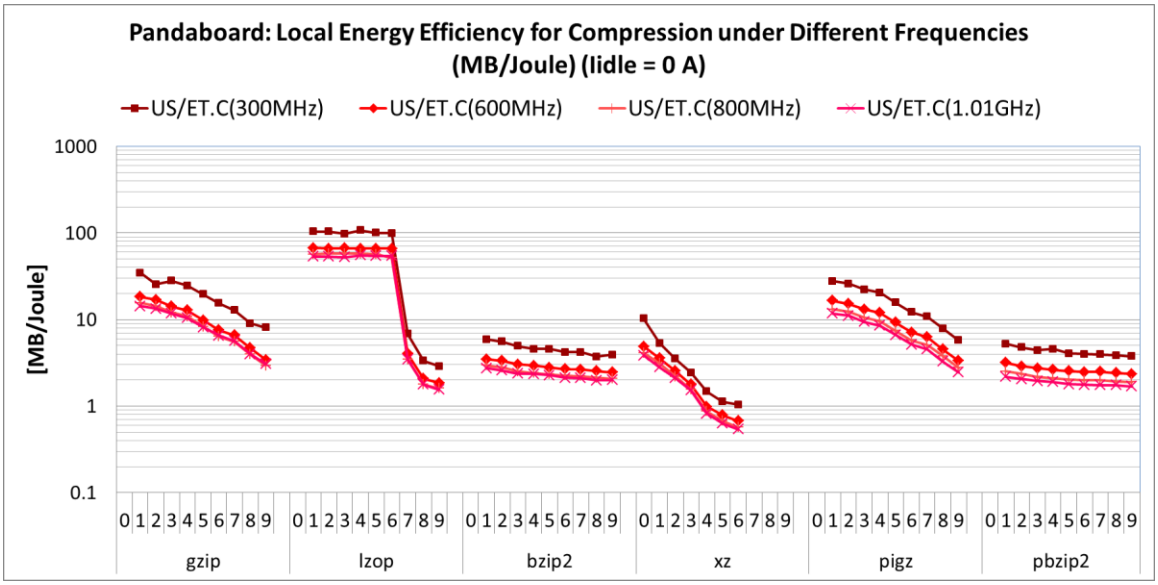
5.4.1.2 Energy Efficiency

Figure 5.14 and Figure 5.15 show the compression and decompression energy efficiency on the Local experiment when I_{idle} is set to 0 and 0.25 A.

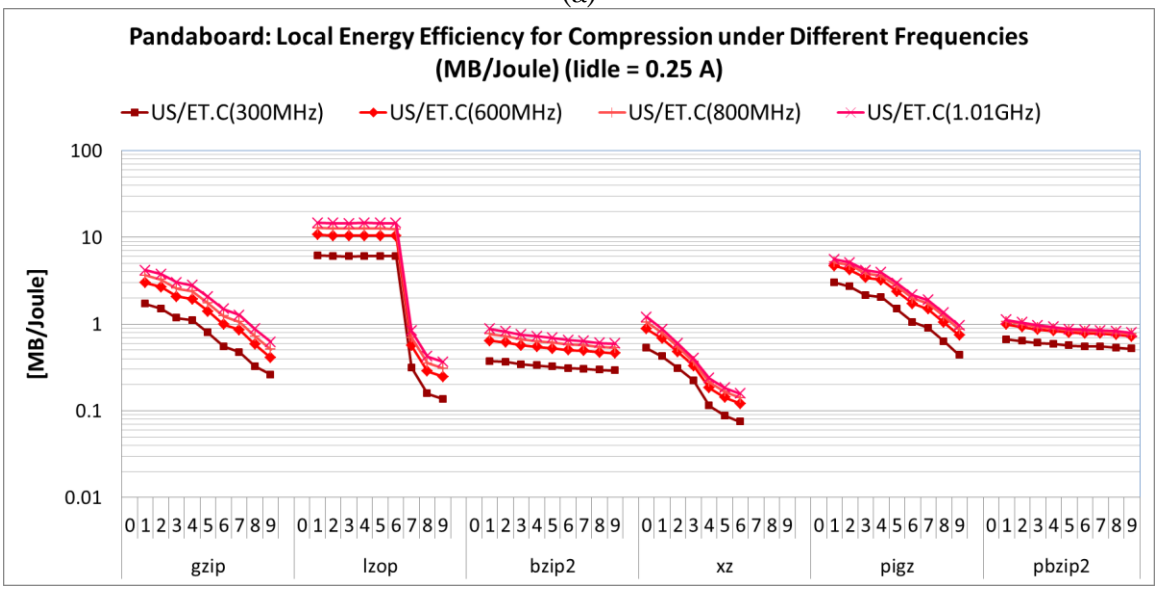
For the compression tasks, the lowest frequency is the most energy efficient choice across all compression utilities when I_{idle} = 0 A (Figure 5.14(a)). The highest energy efficiency is achieved by lzop across all frequency levels, achieving ~105 MB/Joule on 300MHz, and ~50 MB/Joule on 1.01GHz. Following lzop, pigz and gzip come in second for having higher energy efficiency across all frequency levels when compared to other utilities.

The outlook of the results for the energy efficiency of the compression tasks is changing with an increase of the idle current. Figure 5.14(b) shows energy efficiency trends when the idle current is set to 0.25 A (the results for 0.5 A and 0.75 A are similar). Oppositely to the case when I_{idle} = 0 A, the energy efficiency of the compres-

sion utilities increase for higher frequencies, achieving the best energy efficiency at the highest frequency of 1.01 GHz.



(a)

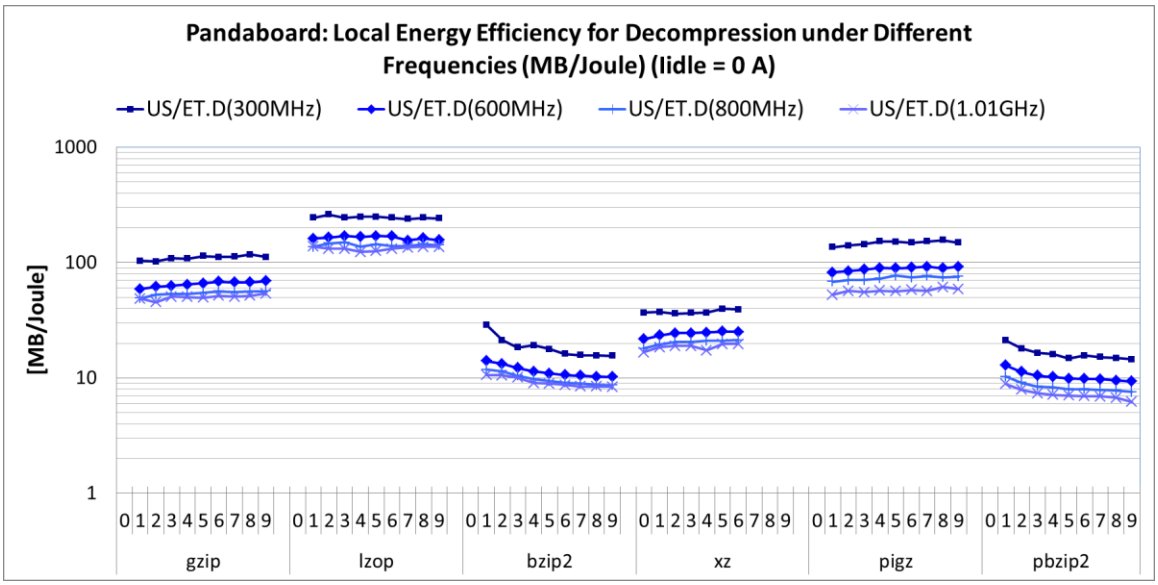


(b)

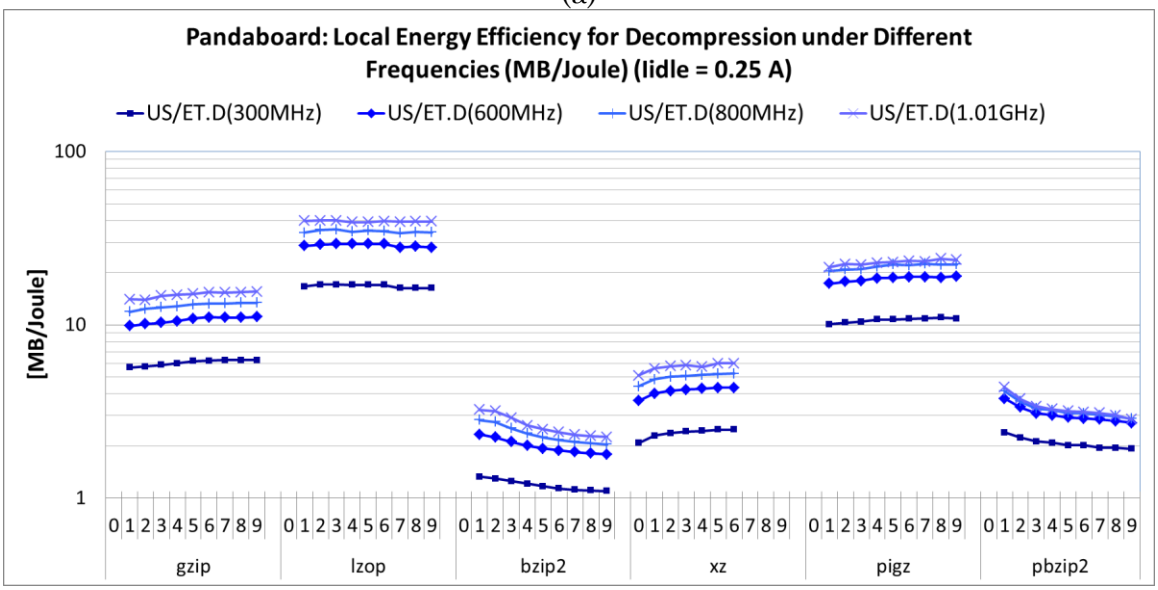
Figure 5.14 Pandaboard: Local Energy Efficiency for Compression under Different Frequencies

For the decompression tasks, the lowest frequency is most energy efficient choice across all decompression utilities when I_{idle} = 0 A (Figure 5.15(a)). The highest energy efficiency is achieved by lzop across all frequency levels, achieving ~260 MB/Joule on 300MHz, and ~137 MB/Joule on 1.01GHz. Following lzop, pigz and gzip come in second for having higher energy efficiency across all the frequency levels when compared to other utilities.

The outlook of the results for energy efficiency of the decompression tasks is changing with an increase of the idle current. Figure 5.15(b) shows energy efficiency trends for the decompression tasks when the idle current is set to 0.25 A. Oppositely to the case when I_{idle} = 0 A, the energy efficiency of the decompression utilities increase for the higher frequencies, achieving the best energy efficiency at the highest frequency of 1.01 GHz.



(a)



(b)

Figure 5.15 Pandaboard: Local Energy Efficiency for Decompression under Different Frequencies

5.4.2 Wired

5.4.2.1 Compression and Decompression Throughputs

Figure 5.16 and Figure 5.17 show the compression and decompression throughput in the Wired experiment. All utilities benefit from higher clock frequency.

The highest compression throughput across all frequencies is achieved by lzop, achieving 11.01 MB/sec on 1.01GHz and 3.73 MB/sec on 300MHz (Figure 5.16). Following lzop, pigz and gzip come in second and third. The throughput of raw network transfer (upload) is highest on 1.01GHz.

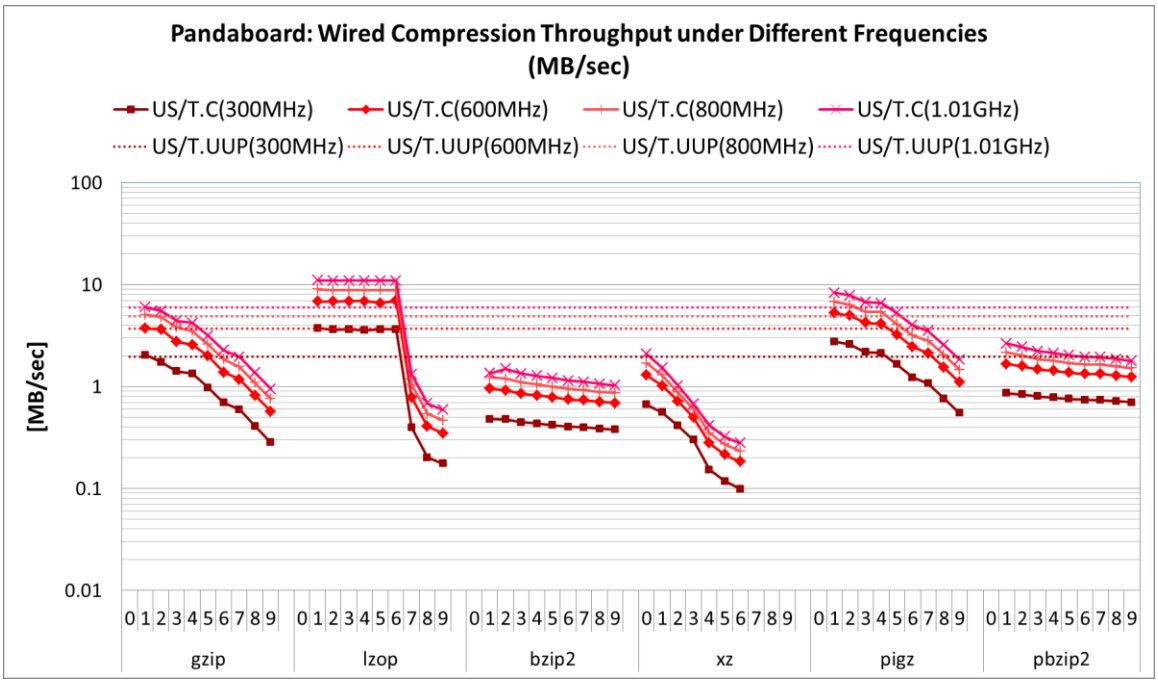


Figure 5.16 Pandaboard: Wired Compression Throughput under Different Frequencies

The highest decompression throughput across all frequencies is achieved by pigz -9, achieving ~23.4 MB/sec on 1.01GHz and 8.04 MB/sec on 300MHz (Figure 5.17). Following pigz, gzip and lzop come in second and third for having higher throughput for all frequency levels when compared to other utilities (gzip -9 with 22.59 MB/sec at 1.01GHz and ~7 MB/sec on 300MHz and lzop -9 with 20.88 MB/sec on 1.01GHz and ~7 MB/sec at 300MHz). The throughput of raw network transfer (download) is highest on 1.01GHz.

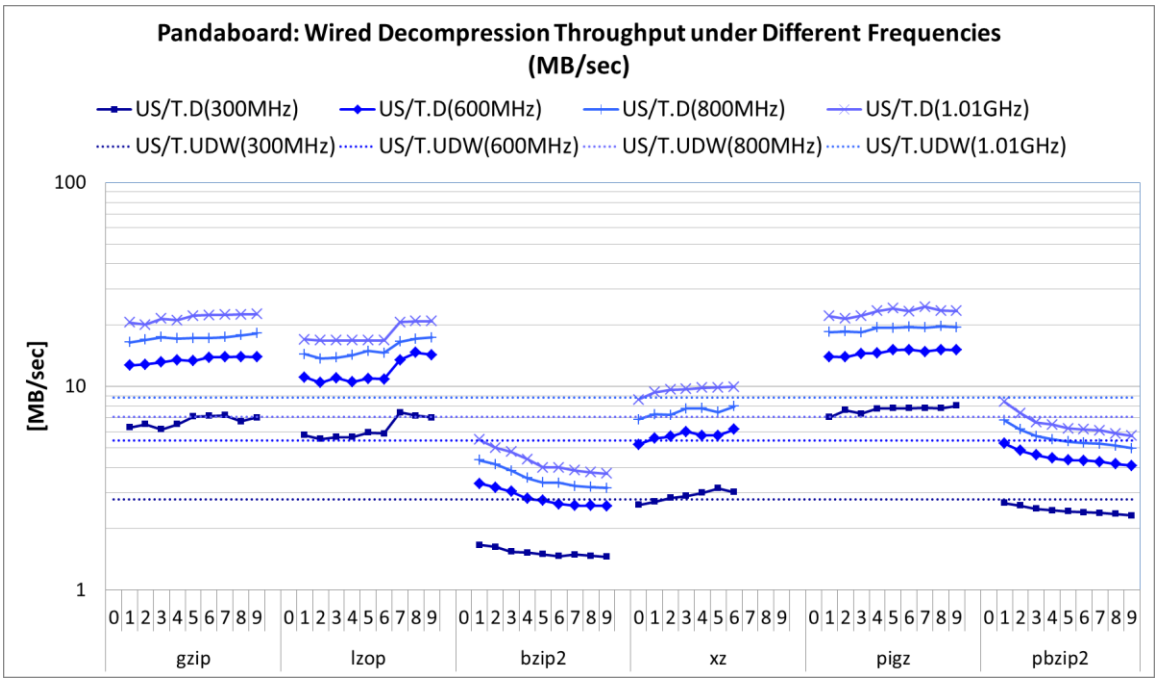


Figure 5.17 Pandaboard: Wired Decompression Throughput under Different Frequencies

Figure 5.18 shows a comparison between throughput ratios and frequency ratios for compression and decompression on the Wired experiment. The throughput

and frequency ratios are calculated in the same way as shown in Section 5.4.1.1. Similarly to the Local experiment, utilities such as gzip, lzop and pigz have the throughput ratios close to the corresponding frequency ratios but deviations are present especially for the lowest frequency ratio (300 MHz) . The same observation is made for xz during decompression. The higher compression levels of bzip2 and pbzip2 have lower throughput ratios when compared with frequency ratios. The same observation can be made for xz with higher compression levels. Having a throughput ratio lower than the corresponding frequency ratio indicates a non-linear throughput change with the frequency scaling on higher compression levels.

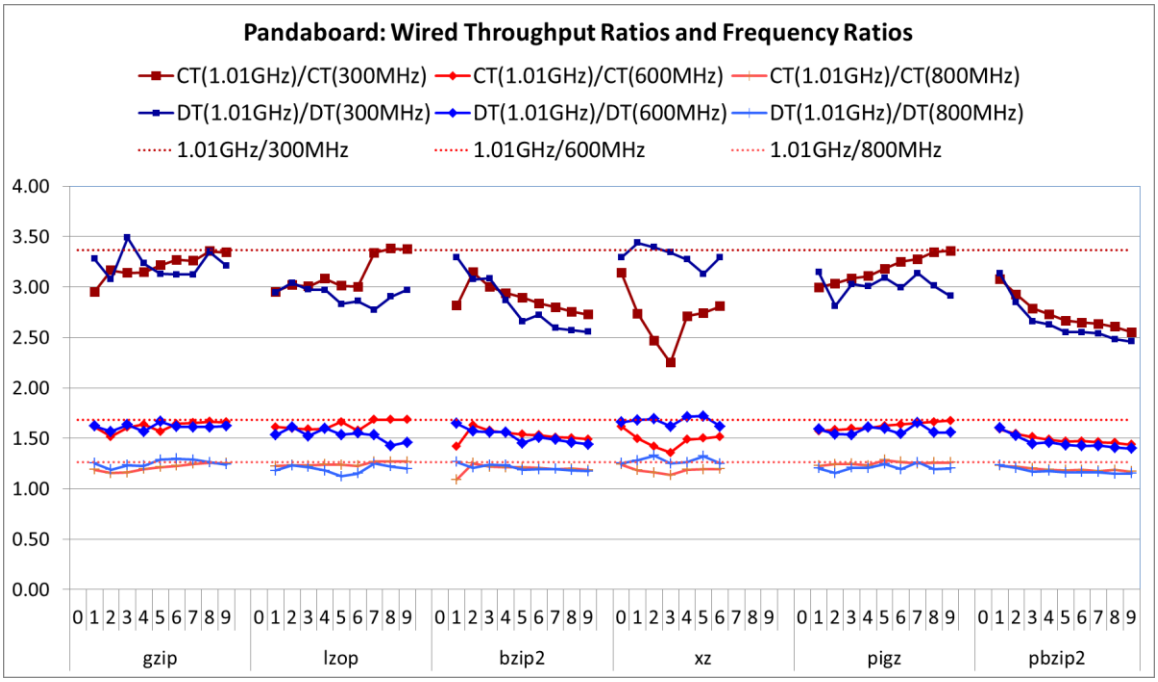


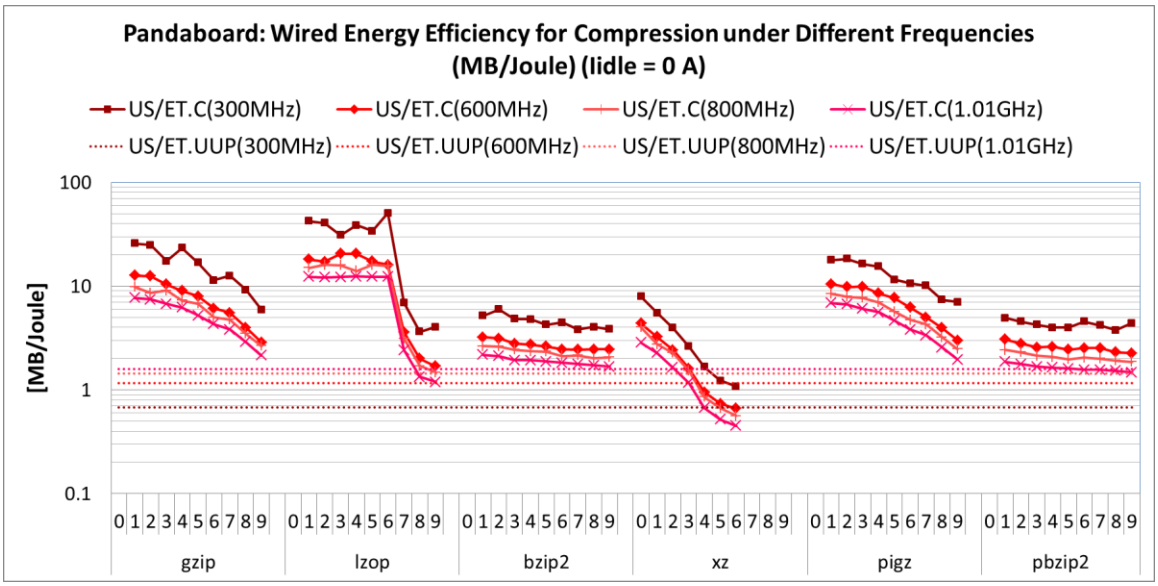
Figure 5.18 Pandaboard: Wired Throughput Ratios and Frequency ratios

5.4.2.2 Energy Efficiency

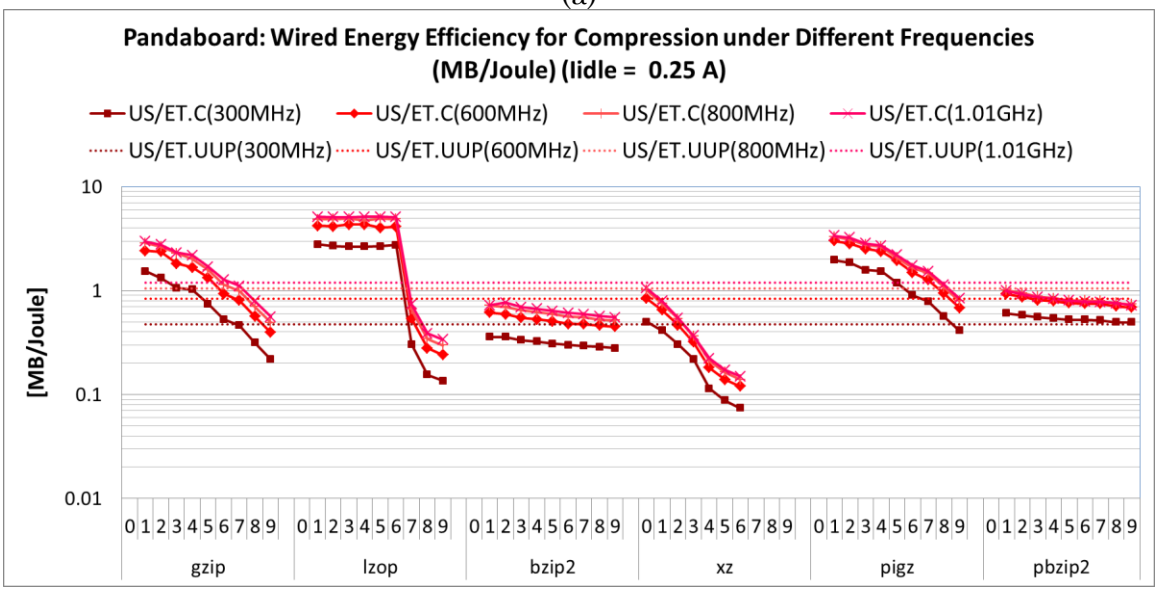
Figure 5.19 and Figure 5.20 show the compression and decompression energy efficiency on the Wired experiment when I_{idle} is set to 0 and 0.25 A, respectively.

The lowest frequency is the most energy efficient choice across all compression tasks when I_{idle} = 0 A (Figure 5.19(a)). The highest energy efficiency is achieved by lzop across all frequency levels, achieving ~45 MB/Joule on 300MHz, and ~12.3 MB/Joule on 1.01GHz. Following lzop, pigz and gzip come in second and third for having higher energy efficiency for all frequency levels when compared to other utilities. The energy efficiency of the raw network upload, on other hand, is highest on 1.01GHz.

The results for energy efficiency of compression tasks change with an increase of the idle current. Figure 5.19(b) shows the energy efficiency when the idle current is set to 0.25 A. The energy efficiency of the compression tasks increase with an increase in the clock frequency, achieving the best energy efficiency at the highest frequency of 1.01 GHz. The energy efficiency of raw file download follows the same trend.



(a)



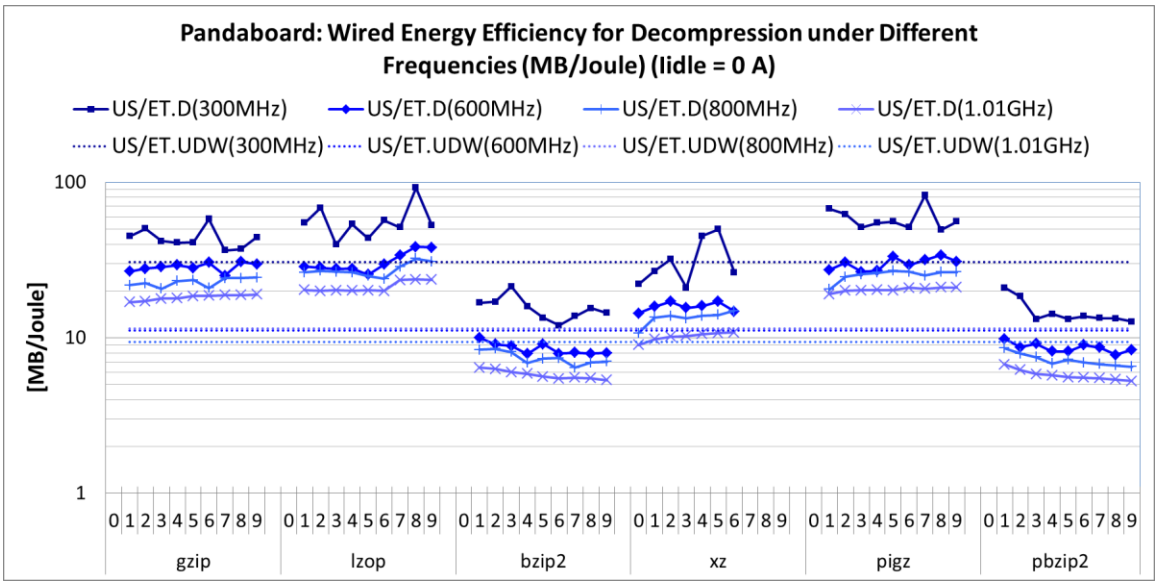
(b)

Figure 5.19 Pandaboard: Wired Energy Efficiency for Compression under Different Frequencies

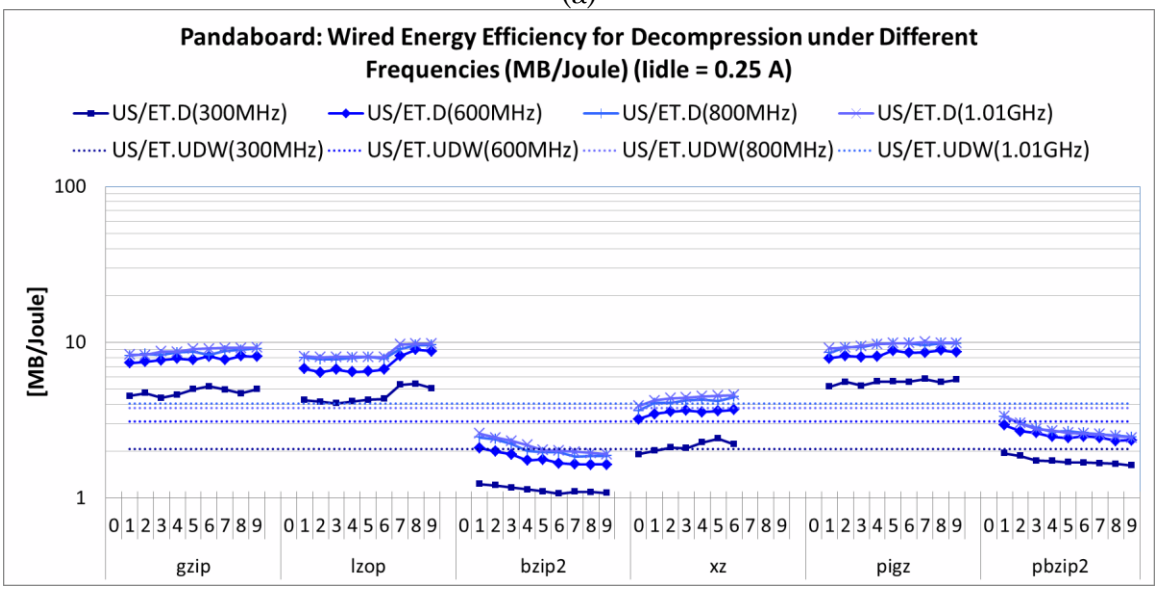
The lowest frequency is the most energy efficient choice across all decompression utilities when I_{idle} = 0 A (Figure 5.20(a)). The highest energy efficiency is achieved by lzop across all frequency levels, achieving from ~60 to 90 MB/Joule on

300MHz, and ~23.6 MB/Joule on 1.01GHz. Following lzop, pigz and gzip come in second and third for having higher energy efficiency across all frequency levels when compared to the other utilities. The energy efficiency of the raw file download is highest for the 300MHz clock frequency.

The energy efficiency of the decompression tasks is changing with an increase of the idle current. Figure 5.20(b) shows energy efficiency trends for decompression when the idle current is set to 0.25 A. The energy efficiency of the decompression utilities increases for higher clock frequencies, achieving the best energy efficiency at the highest frequency of 1.01 GHz. The energy efficiency of the raw file download peaks at the highest clock frequency.



(a)



(b)

Figure 5.20 Pandaboard: Wired Energy Efficiency for Decompression under Different Frequencies

5.4.3 Wireless

5.4.3.1 Compression and Decompression Throughputs

Figure 5.21 and Figure 5.22 show the compression and decompression throughput in the Wireless experiment. All utilities benefit from higher clock frequency.

The highest compression throughput across higher frequencies (800MHz and 1.01GHz) is achieved by pigz -1, achieving 5.1 MB/sec on 1.01 GHz (Figure 5.21). The highest compression throughput across lower frequencies (300MHz and 600MHz) is achieved by lzop -1 to 6, achieving 2.8 MB/sec on 300MHz. The throughput of raw network transfer (upload) is highest on 1.01GHz.

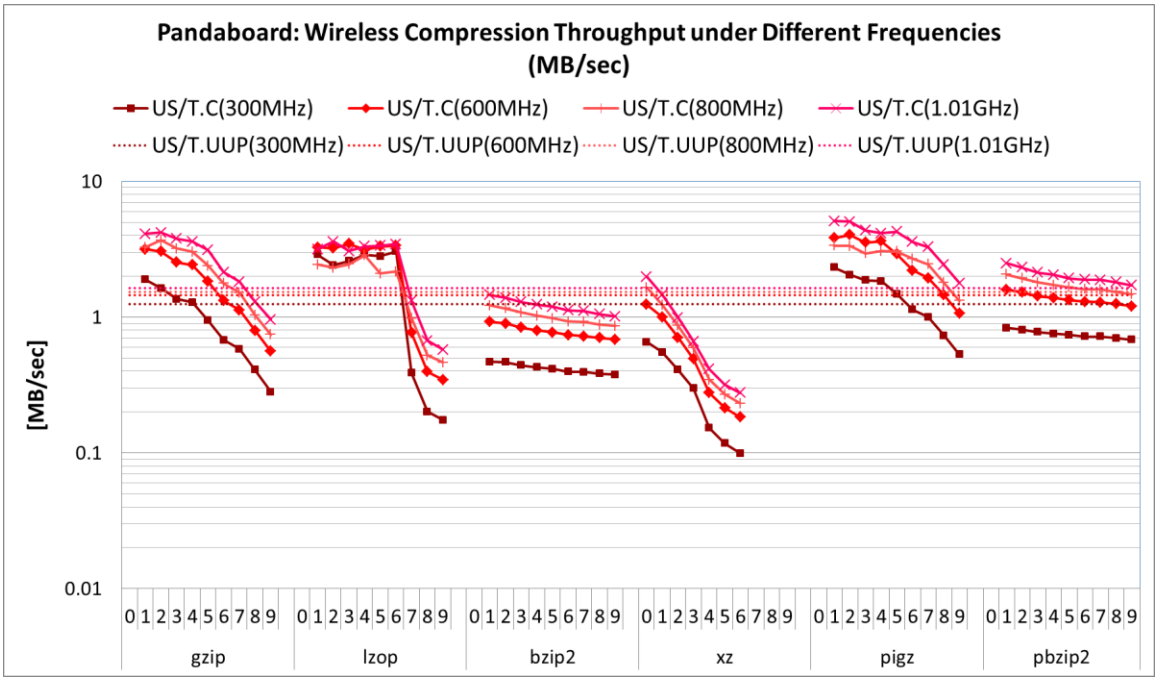


Figure 5.21 Pandaboard: Wireless Compression Throughput under Different Frequencies

The highest decompression throughput across higher frequencies is achieved by xz, achieving 6.49 MB/sec on 1.01GHz (Figure 5.22). The highest decompression throughput on the lowest frequency is achieved by pigz, gzip and lzop. The throughput of raw network transfer (download) is highest on 300MHz.

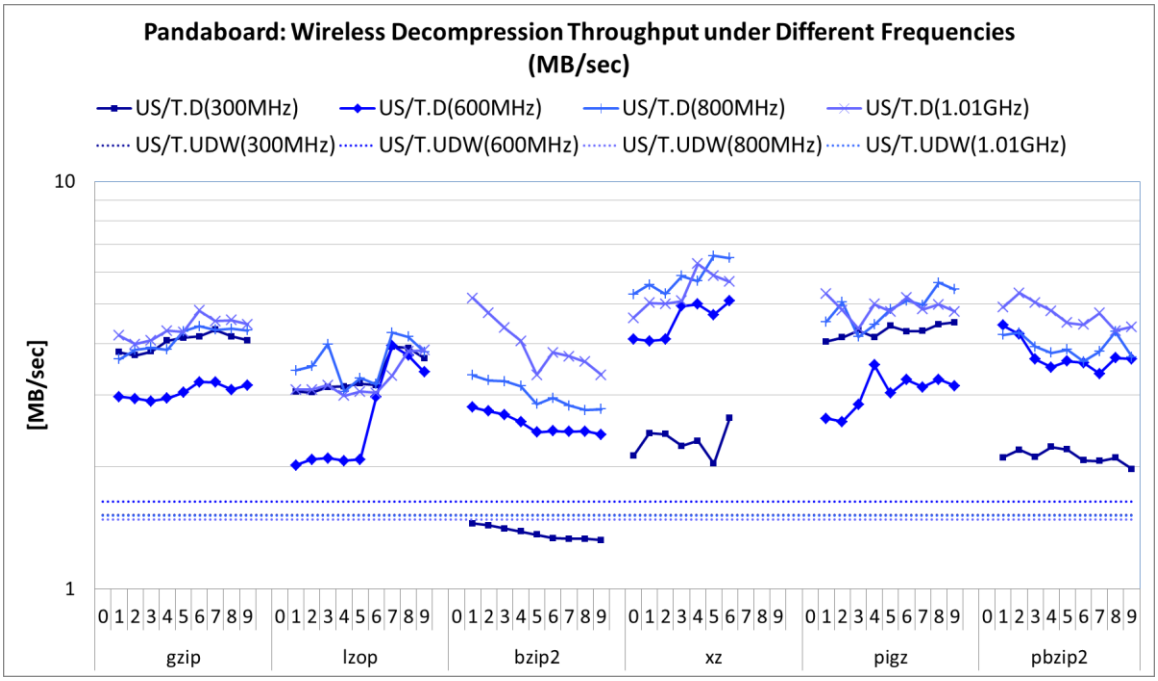


Figure 5.22 Pandaboard: Wireless Decompression Throughput under Different Frequencies

Figure 5.23 shows a comparison between throughput ratios and frequency ratios for compression and decompression on the Wireless experiment. Derivation of throughput and frequency ratios follows same example made before in Section 5.4.1.1. The distribution of ratios, however, differs on the Wireless experiment from

those demonstrated for the Local and Wired experiments in Section 5.4.1 and Section 5.4.2. Now, only some compression utilities and only certain compression levels achieve throughput ratio that is equal to or very close to the corresponding frequency ratio. This is now only true for compression utilities such as gzip -5 to -9, lzop -7 to -9, pigz -6 to -9, bzip2 -1 and pbzip2 -1. For compression, greatest benefit from downward frequency scaling can be seen in lzop -1 to -6 for 1.01 GHz to 300 MHz case, with T.C(1.01GHz)/T.C(300MHz) being ~1.2 while 1.01GHz/600MHz ratio is 3.37. For decompression, the downward frequency scaling is beneficial to almost all utilities, with throughput ratios of all utilities, except of bzip2, being much lower than the corresponding frequency ratio.

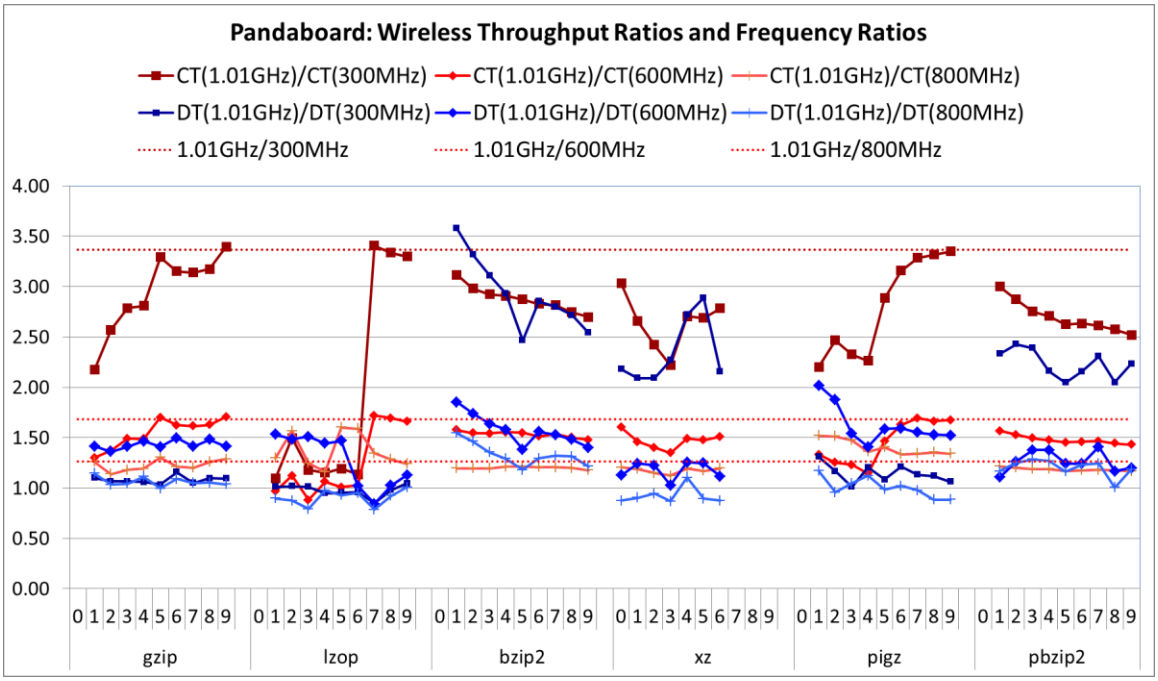


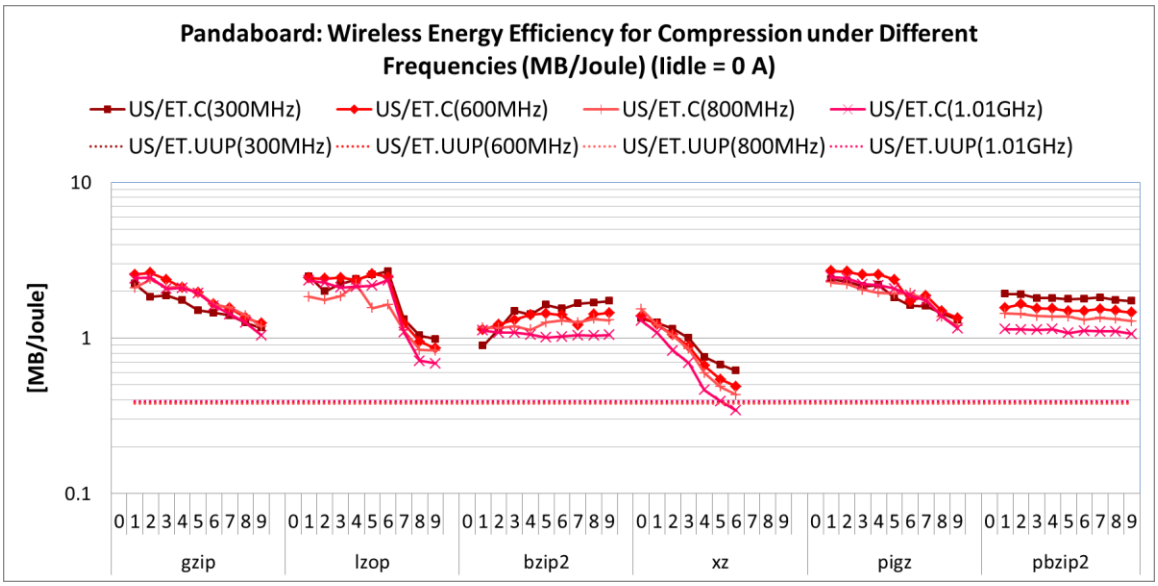
Figure 5.23 Pandaboard: Wireless Throughput Ratios and Frequency Ratios

5.4.3.2 Energy Efficiency

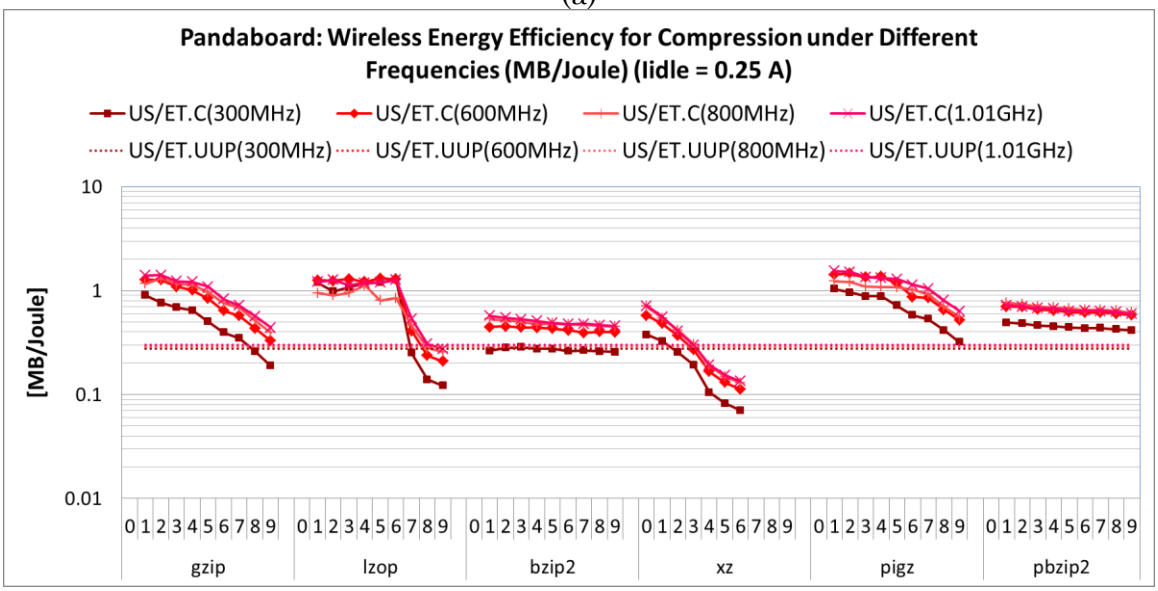
Figure 5.24 and Figure 5.25 show the compression and decompression energy efficiency on the Wireless experiment when I_{idle} is set to 0 and 0.25 A.

The lowest frequency is the most energy efficient choice across selected compression utilities when I_{idle} = 0 A (Figure 5.24(a)). The utilities that benefit from lowest frequency are pbzip2, bzip2 and xz. The utilities that benefit from higher frequencies are pigz, gzip and lzop (with small differences between frequencies 600MHz, 800MHz and 1.01GHz). The highest energy efficiency is achieved by lower levels of pigz, lzop -1 to -6, and lower levels of gzip across all frequency levels. The energy efficiency of raw network energy efficiency (upload) does not change with frequency scaling.

The results for energy efficiency of compression tasks change with an increase of the idle current. Figure 5.24(b) shows energy the efficiency when the idle current is set to 0.25 A. The energy efficiency of the compression tasks increase with an increase in the clock frequency, achieving the best energy efficiency at the highest frequency of 1.01 GHz. The energy efficiency of raw network transfer (download) does not change with frequency scaling.



(a)



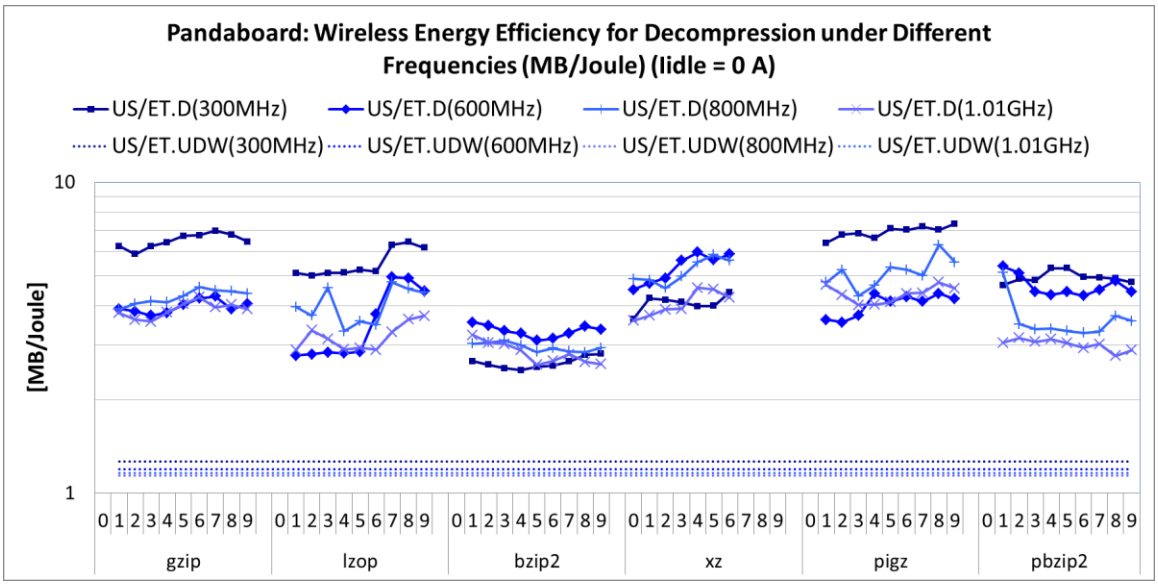
(b)

Figure 5.24 Pandaboard: Wireless Energy Efficiency for Compression under Different Frequencies

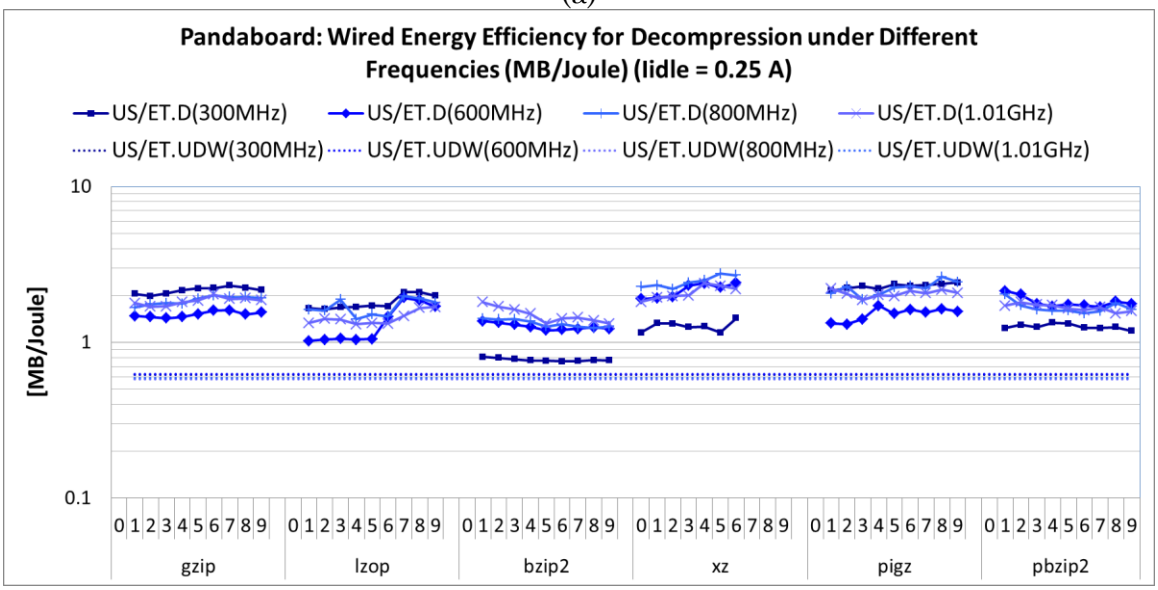
The lowest frequency is most energy efficient choice only for selected decompression utilities when I_{idle} = 0 A (Figure 5.25(a)). The highest energy efficiency is achieved by lzop across all frequency levels, achieving 7.34 MB/Joule on 300MHz,

and 4.55 MB/Joule on 1.01GHz. Following lzop, pigz and gzip come in second and third for having higher energy efficiency across all frequency levels when compared to other utilities. The energy efficiency of raw network energy efficiency (upload) does not change with frequency scaling.

The energy efficiency of the decompression tasks is changing with an increase of the idle current. Figure 5.25(b) shows energy efficiency trends for decompression when the idle current is set to 0.25 A. Similarly to the case when $I_{idle} = 0$ A, the lowest frequency is most energy efficient choice only for selected decompression utilities, such as pigz, gzip and lzop. However, the difference between the energy efficiency at the highest and the lowest frequency is much smaller. For this reason, the best overall energy efficiency is achieved by xz at higher frequencies (600 MHz, 800 MHz, 1.01 GHz). The energy efficiency of raw file download does not change with frequency scaling.



(a)



(b)

Figure 5.25 Pandaboard: Wireless Energy Efficiency for Decompression under Different Frequencies

5.5 Conclusions

The experimental results for the Pandaboard platform show that compression is best at the lowest compression levels, and decompression is best at the highest

compression level (for exception of bzip2 and pbzip2) for both the throughput and energy efficiency.

Table 5.1 summarizes the throughput results. lzop performs the best for compression and decompression in the Local experiment and for compression in the Wired experiment. The best throughput for decompression in the Wired experiment is achieved by pigz, followed by gzip and then lzop (pigz outperforms lzop by 3.67%). For the Wireless experiment, pigz with -1 performs the best for compression and xz with -4 performs the best for decompression.

Table 5.1 Throughputs on Pandaboard @ 1.01GHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
	Best Utility	*Th.C [MB/s]*	*Th.UUP [MB/s]*	*Best Utility*	*Th.D [MB/s]*	*Th.UWD [MB/s]*
LOCAL	lzop -1 to -6	25		lzop -1 to -9	70	
WIRED	lzop -1 to -6	11	5.95	pigz -6 to -9	23.5	8.84
WIRELESS	pigz -1	5.1	1.64	xz -4	6.28	1.52

Table 5.2 shows the energy efficiency. lzop is the most energy-efficient for both the Local and Wired experiment for compression and decompression. pigz, gzip and xz outperform lzop in the Wireless experiment. For compression, pigz has the best energy efficiency, followed by gzip and lzop. For decompression, when I_{idle} is 0 A, pigz has the best energy efficiency, followed by xz, gzip, and lzop. However, when I_{idle} is 0.25, 0.5 or 0.75, xz overtakes pigz in the energy efficiency. The results show that compressed network transfers are more energy efficient that raw network transfers. In the Wired experiment, the most energy efficient compressed upload with pigz -1

achieves 12.4 MB/J, which ~7.8 times more energy efficient than 1.59 MB/J achieved with the uncompressed upload (assuming Iidle = 0 A). The most energy-efficient decompressed download using lzop with -9 achieves 23.5 MB/J, which is ~2.5 times better than the uncompressed download that achieves 9.43 MB/J. In the Wireless experiment, the most energy-efficient upload using pigz with -1 achieves 2.5 MB/J, compared to 0.39 MB/J achieved by the uncompressed upload (> 6 times improvement). Similarly, the decompressed download offers almost 4 times higher energy efficiency than the uncompressed download.

Table 5.2 Energy Efficiency on Pandaboard @ 1.01GHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
LOCAL	*Best Utility*	*EE.C [MB/J]*	*EE.UUP [MB/J]*	*Best Utility*	*EE.D [MB/J]*	*EE.UDW [MB/J]*
I_{idle} = 0 A	lzop -1 to -6	55		lzop -6 to -9	137	
I_{idle} = 0.25 A	lzop -1 to -6	14.5		lzop -6 to -9	40	
I_{idle} = 0.5 A	lzop -1 to -6	8.5		lzop -1 to -9	23	
WIRED						
I_{idle} = 0 A	lzop -1 to -6	12.4	1.59	lzop -7 to -9	23.5	9.43
I_{idle} = 0.25 A	lzop -1 to -6	5.1	1.19	pigz -6 to -9	10	4.04
I_{idle} = 0.5 A	lzop -1 to -6	3.2	0.95	pigz -6 to -9	6.5	2.57
WIRELESS						
I_{idle} = 0 A	pigz -1	2.5	0.39	pigz -4 to -7	4.6	1.16
I_{idle} = 0.25 A	pigz -1	1.5	0.30	xz -4 to -6	2.4	0.59
I_{idle} = 0.5 A	pigz -1	1.1	0.25	xz -4 to -6	1.6	0.40

Use of parallel compression utilities such as pigz and pbzip2 offers gains in the throughput and the energy efficiency for the compression and decompression

tasks. Table 5.3 summarizes the throughput and the energy efficiency gains of pigz and pbzip2 when compared to the sequential counterparts for all experimental cases.

Table 5.3 Performance Gains of Parallel Utilities on Pandaboard @ 1.01GHz

	I_{idle} (A)	Throughput Gain (compression/decompression)		
		Local	Wired	Wireless
pigz		~80%	38.19%/3.67%	24.0%/9.7%
pbzip2		~80%	77.98%/53.20%	71.2%/2.8%
		Energy Efficiency Gain (compression/decompression)		
		Local	Wired	Wireless
pigz	0.00	0%/9.9%	0%/0%	0%/11.24%
	0.25	32.86%/52.2%	13.91%/9.9%	10.5%/6.95%
	0.50	48.38%/62.78%	22.06%/9.20%	15.36%/5.94%
	0.75	56.64%/67.65%	25.56%/8.6%	17.33%/5.05%
pbzip2	0.00	0%/0%	0%/0%	0%/0%
	0.25	27.5%/34.49%	37.5%/28.7%	27.1%/~0%
	0.50	43.5%/50.99%	58.13%/37.4%	40.0%/~1%
	0.75	54.05%/58.82%	64.51%/41.26%	44.0%/~1%

The frequency scaling analysis indicates that the compression and decompression throughputs suffer from lower frequency, which can be explained easily by the general observation that the execution time of each utility goes up with lowering of frequency. The energy efficiency when the idle current is 0 A increases when the clock frequency goes down for all utilities in the Local and the Wired experiment and only for the selected utilities in the Wireless (pigz, gzip and lzop). When the idle current is set to a value greater than zero (such as 0.25 A or greater), lowering the clock frequency is not beneficial for all the utilities in the Local and Wired for both the compression and decompression tasks. In the Wireless experiment, lowering the

clock frequency is only beneficial to selected set of utilities in the decompression tasks (pigz, gzip and lzop), and to none in the compression tasks.

CHAPTER 6

RASPBERRY PI RESULTS

This chapter presents the results of the experimental evaluation for the Raspberry Pi platform. Section 0 discusses the compression ratio achieved by the compression utilities for supported compression levels. Section 6.2 discusses the compression and decompression throughputs. Section 6.3 discusses energy efficiency of compression and decompression tasks. Section 6.4 summarizes findings from the Raspberry Pi experiments.

6.1 Compression ratio

The compression ratios for the Raspberry Pi platform are the same as the ratios on the Pandaboard platform reported in Figure 5.1 for reasons of using the same versions of compression and decompression utilities and the same dataset (totalInput.tar) to perform all compression and decompression tasks.

6.2 Compression and Decompression Throughputs

6.2.1 Local

Figure 6.1 shows the overall compression and decompression throughputs for the Local experiment expressed in MB/sec. For all compression utilities, the higher compression levels result in lower throughputs. By far the highest compression throughput of ~9.5 MB/sec is achieved by lzop -1 to -6. The second highest compression throughput from 2.754 to 0.366 MB/sec is achieved by pigz. pigz outperforms gzip (10-16% improvement) in spite of the Raspberry Pi featuring a single core processor because the pigz implementation overlap core compression operations with

input/output operations. In contrast to pigz, pbzip2 does not achieve any speedup in compression when compared to bzip2. The xz and bzip2 utilities achieve significantly lower compression throughputs (e.g., from 0.738 to 0.114 MB/sec for xz and from 0.555 to 0.412 for bzip2).

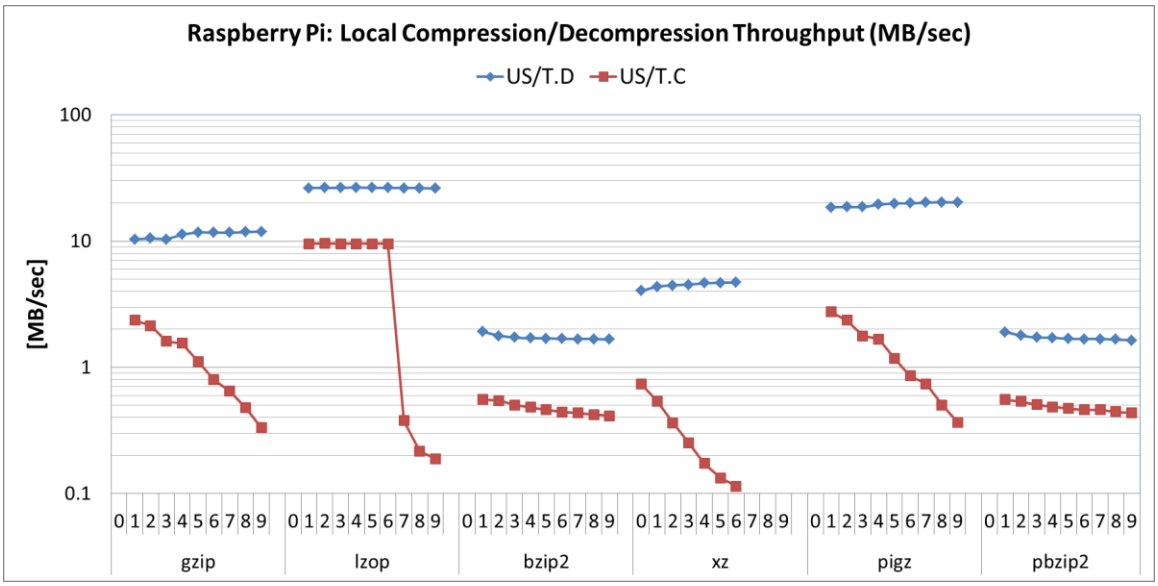


Figure 6.1 Raspberry Pi: Local Compression/Decompression Throughput

The decompression throughputs are much higher than the compression throughputs and are only indirectly dependent on the compression level. The higher compression levels typically result in smaller compressed files, which may increase decompression throughputs because less time is needed to read the input files. Similar to the experimental results on the Pandaboard platform, notable exceptions are bzip2 and pbzip2, where decompression throughputs slightly decrease for higher compression levels, in spite of smaller input files. The highest decompression

throughput of 26.5 MB/sec is achieved by lzop, followed by pigz (18.5 to 20.2 MB/sec) and gzip (10.4 to 11.9 MB/sec). xz achieves 4.0 to 4.7 MB/sec, whereas pbzip2 and bzip2 range from 1.9 to 1.6 MB/sec (both having lower decompression throughputs for higher compression levels). It should be noted that pigz offers improvements in decompression throughputs over its sequential counterpart.

6.2.2 Wired

Figure 6.2 shows the compression and decompression throughputs in the Wired experiment. The dashed lines represent the measured effective network throughput when the uncompressed input files are uploaded to the remote server (US/T.UUP = 3.60 MB/sec) and downloaded from the remote server (US/T.UDW = 4.97 MB/sec).

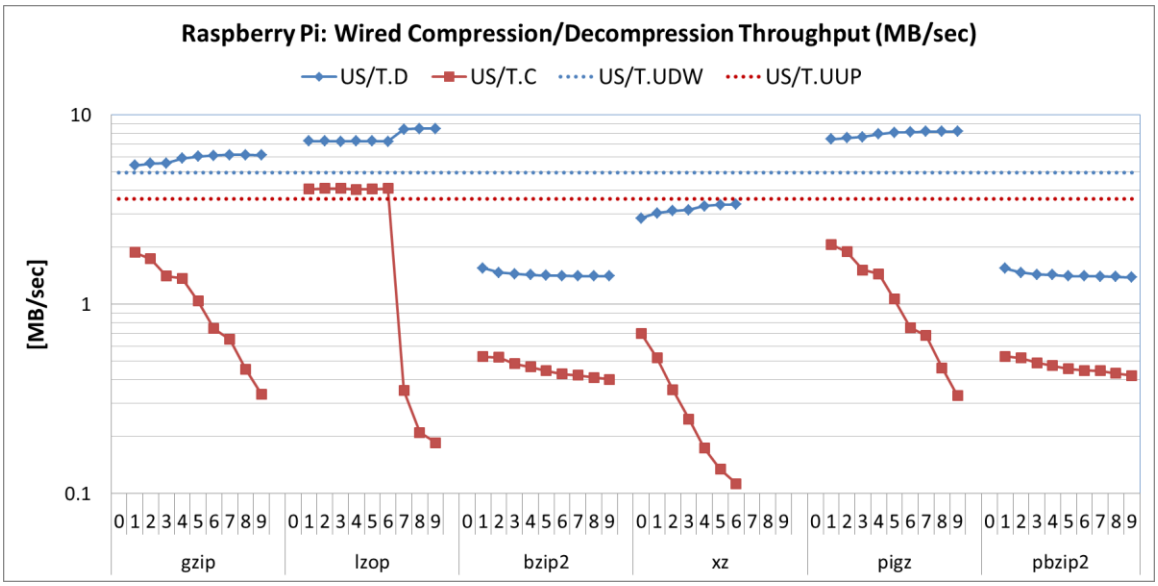


Figure 6.2 Raspberry Pi: Wired Compression/Decompression Throughput

The compression throughput is limited by the effective network throughput and therefore it is always below the CR*(US/T.UUP). For example, lzop -1 (through -6) plateaus at 4 MB/sec, which is below 2.07*3.60 = 7.5 MB/sec (the compression ratio for lzop -1 is 2.07). The effective compression throughput in this case is thus significantly below the 9.5 MB/sec measured in the Local experiment. However, for lzop with -7, -8, and -9, where the original compression throughput is lower than the upload network throughput (3.60 MB/sec), the compression throughputs remain unchanged relative to those measured in the Local experiment. Similar observations can be made about the other compression utilities. For gzip and pigz with -1, the compression throughputs are 1.87 and 2.06 MB/sec, respectively, well below the maximum achievable 9.54 MB/sec (2.65*3.60, where 2.65 is the compression ratio for gzip and pigz with -1). Even with Raspberry Pi being a single-core system, pigz with low compression levels offers higher compression throughput relative to gzip (~10% on level -1). On higher compression levels, pigz and gzip achieve similar throughputs. Similarly to the Local experiment, pbzip2 does not offer higher compression throughput relative to bzip2 (both achieving from ~0.53 to ~0.41 MB/sec). When compared to the throughput for uploading the uncompressed dataset, only lzop with -1 to -6 provide an increased effective network throughput, whereas the other combinations do not appear to be beneficial.

The decompression throughputs are also limited by the effective network throughput, resulting in lower effective decompression throughputs, which are below CR*(US/T.UDW). For example, lzop with -9 achieves a decompression throughput of ~8.45 MB/sec, which is 65% of the maximum achievable (2.62*4.97 = 13.02 MB/sec) and 32% of the 26.19 MB/sec measured in the Local experiment. gzip with -9 achieves ~6.12 MB/sec and pigz with -9 achieves ~8.16 MB/sec. Just like in the Local

experiment, pigz outperforms gzip on almost all compression levels by ~35%. gzip and pigz do not outperform lzop, however pigz is within 3% from lzop on highest levels. The three utilities (gzip, lzop and pigz) effectively increase the available network throughput (their throughputs are above the US/T.UDW line) and decrease the download time relative to the time needed to download uncompressed files from the remote server. pbzip2 and bzip2 (from 1.54 to 1.40 MB/sec) and xz (from 2.84 to 3.60 MB/sec) fall far below the available network throughput for downloads (4.97 MB/sec).

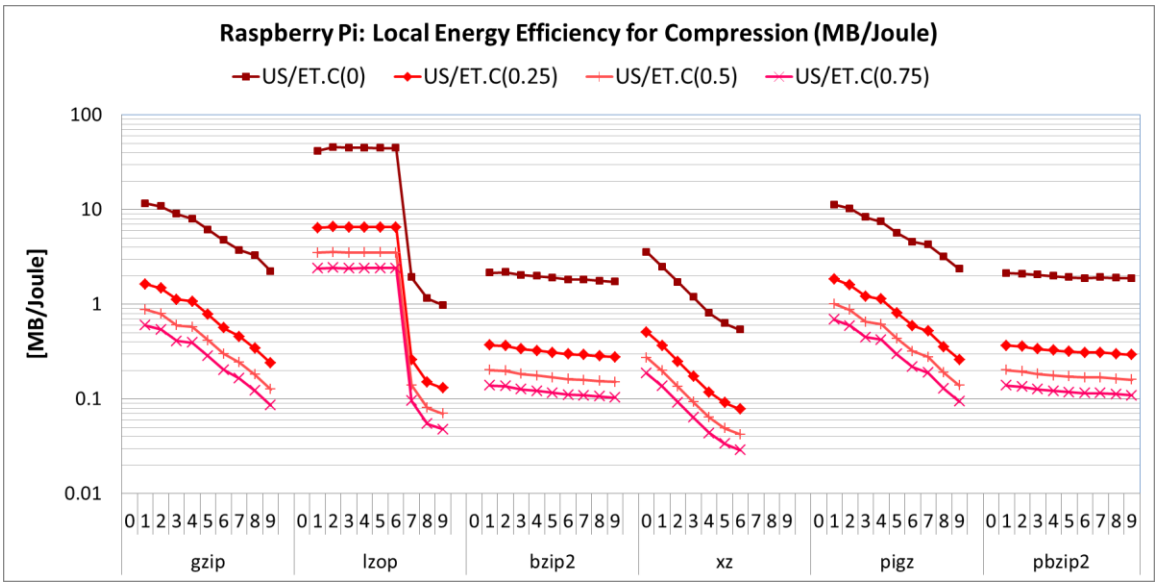
6.3 Energy Efficiency

6.3.1 Local

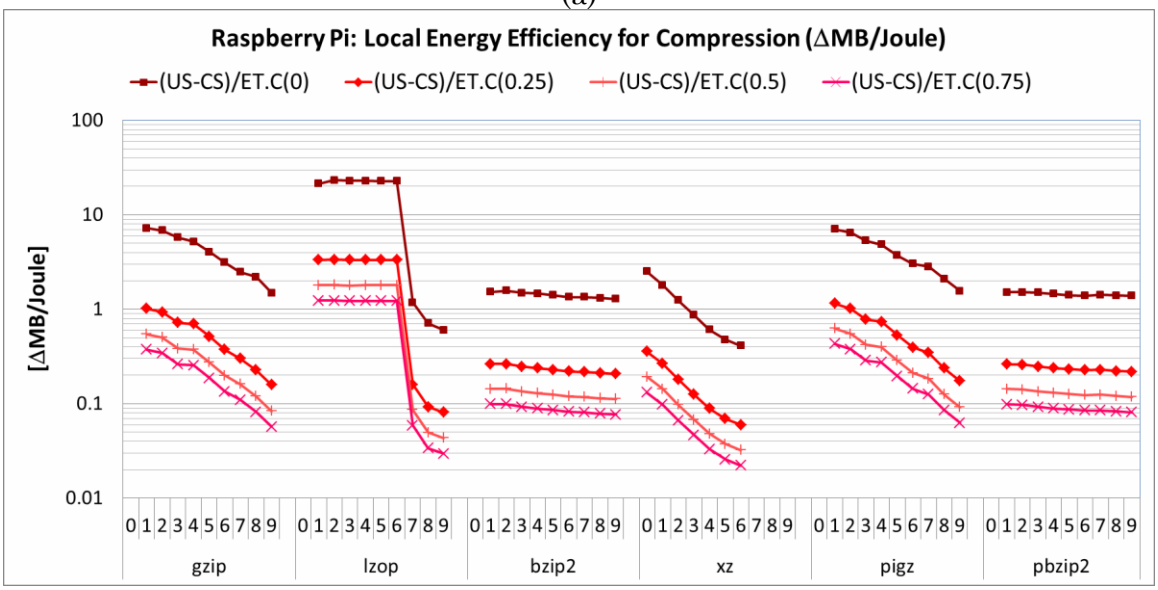
Figure 6.3 and Figure 6.4 show the energy efficiency for the compression and decompression tasks for the Local experiment reported in MB/J (US/ET.C and US/ET.D) and in ΔMB/J (|US-CS|/ET.C and |US-CS|/ET.D) as a function of the idle current I_{idle} (I_{idle}={0, 0.25, 0.5, 0.75} A).

The energy efficiency for the compression tasks varies widely for different utilities and for different compression levels within each utility, as shown in Figure 6.3. The most energy efficient compression utility by far is lzop with compression levels -1 to -6 regardless of the idle current; it achieves ~44.9 MB/J (MB/joule) for I_{idle}=0 A, ~6.5 MB/J for I_{idle}=0.25 A, and 3.5 MB/J for I_{idle}=0.5 A. Distant second and third are gzip and pigz with -1 achieving ~11.6 MB/J and ~11.2 MB/J for I_{idle}=0. Following the trends in compression throughputs, higher compression levels for gzip, pigz, and lzop result in a dramatic decrease in energy efficiency (e.g., down to 0.97 MB/J for lzop with -9). pigz is more energy efficient than its sequential counterpart when $I_{idle} \neq 0$ (by ~14%) because they reduce the compression time. However, if we

consider only the energy efficiency when I_{idle} = 0 A (US/ET.C(0)), the parallel implementation is slightly less energy efficient. pbzip2, bzip2 and xz exhibit low energy efficiencies making them least attractive choice for compression. The alternative energy efficiency expressed in ΔMB/J follows similar trends as the regular energy efficiency.



(a)

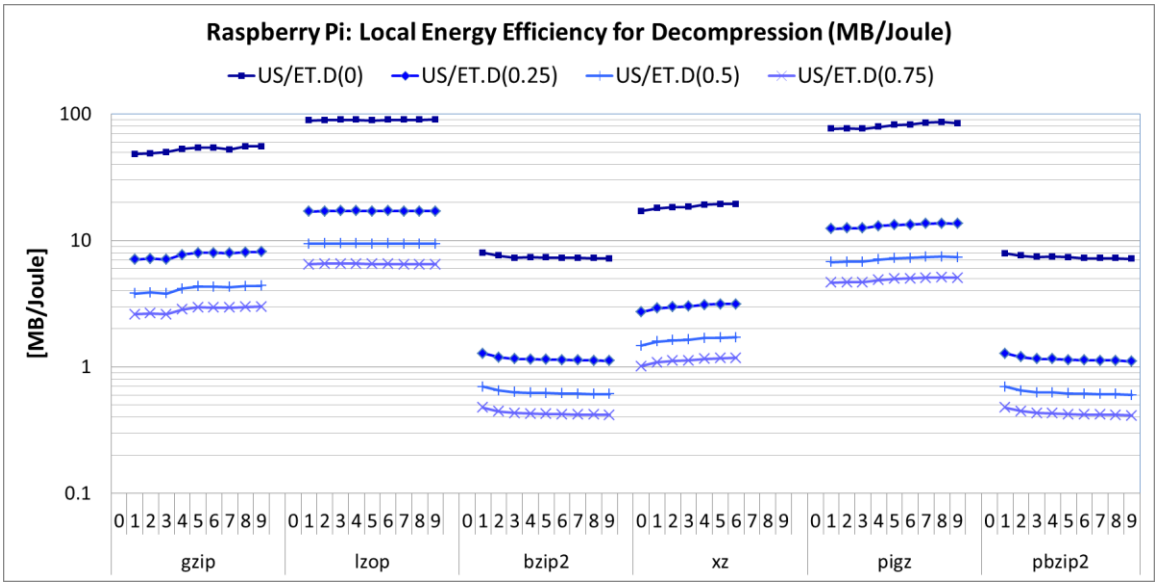


(b)

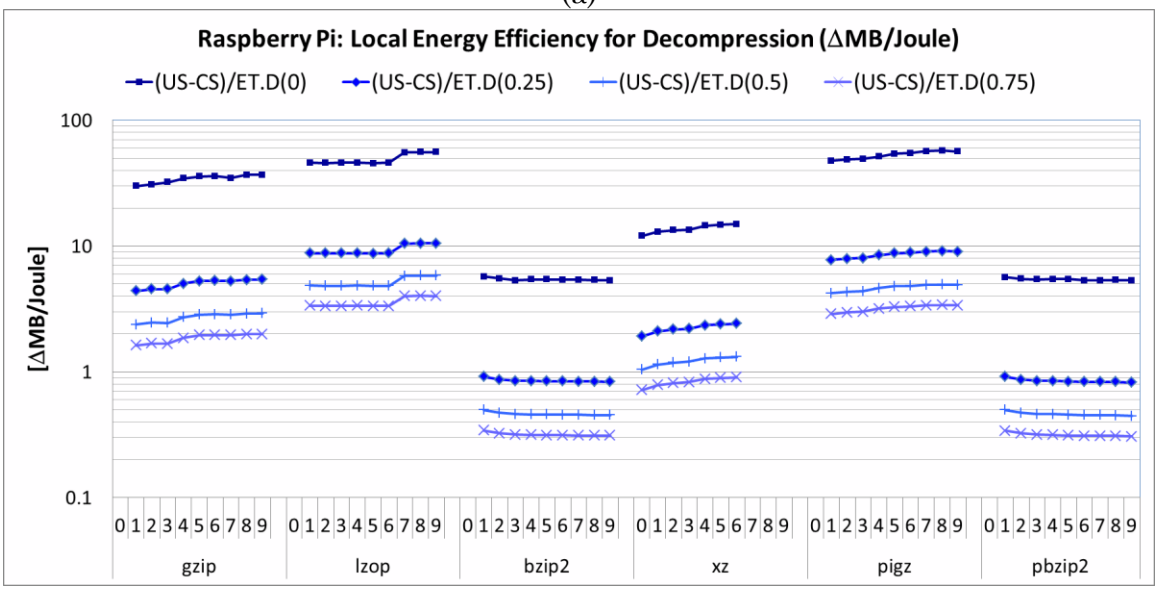
Figure 6.3 Raspberry Pi: Local Energy Efficiency for Compression

The energy efficiency of the decompression tasks varies widely for different utilities as shown in Figure 6.4. The energy efficiency is relatively stable for individual utilities – it increases slightly for higher compression levels for all utilities except bzip2 and pbizp2. Thus, US/ET.D(0) is ~90.5 MB/J for lzop, ~55.4 MB/J for gzip,

~86.5 for pigz, and just below ~8 MB/J for bzip2/pbzip2. lzop emerges as the most energy-efficient choice in spite of its lower compression ratio. These observation hold for the alternative definition of energy efficiency defined as (US-CS)/ET.D.



(a)



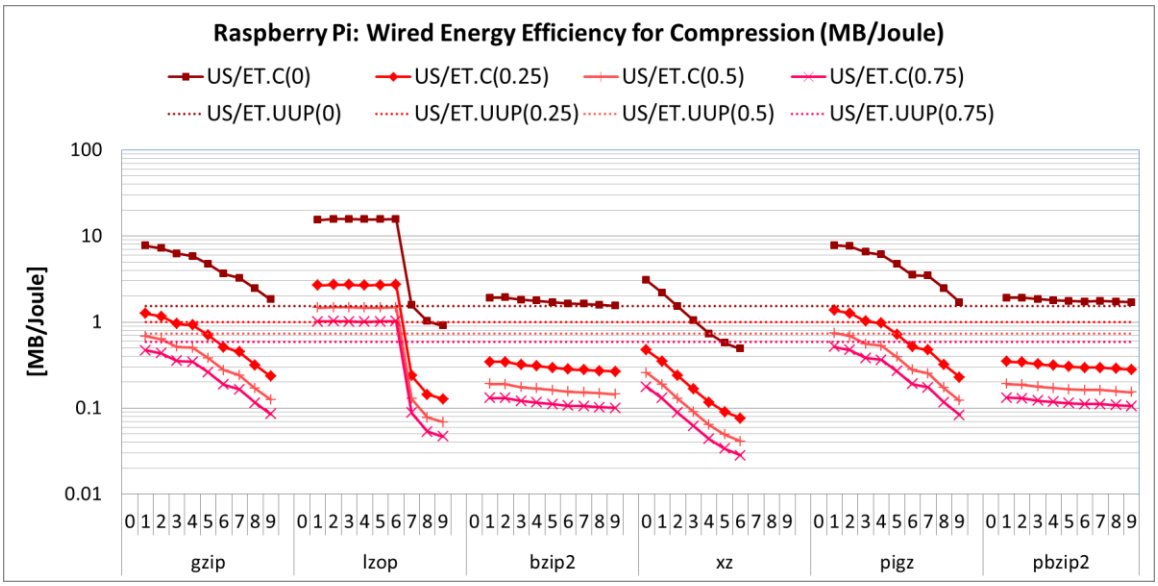
(b)

Figure 6.4 Raspberry Pi: Local Energy Efficiency for Decompression

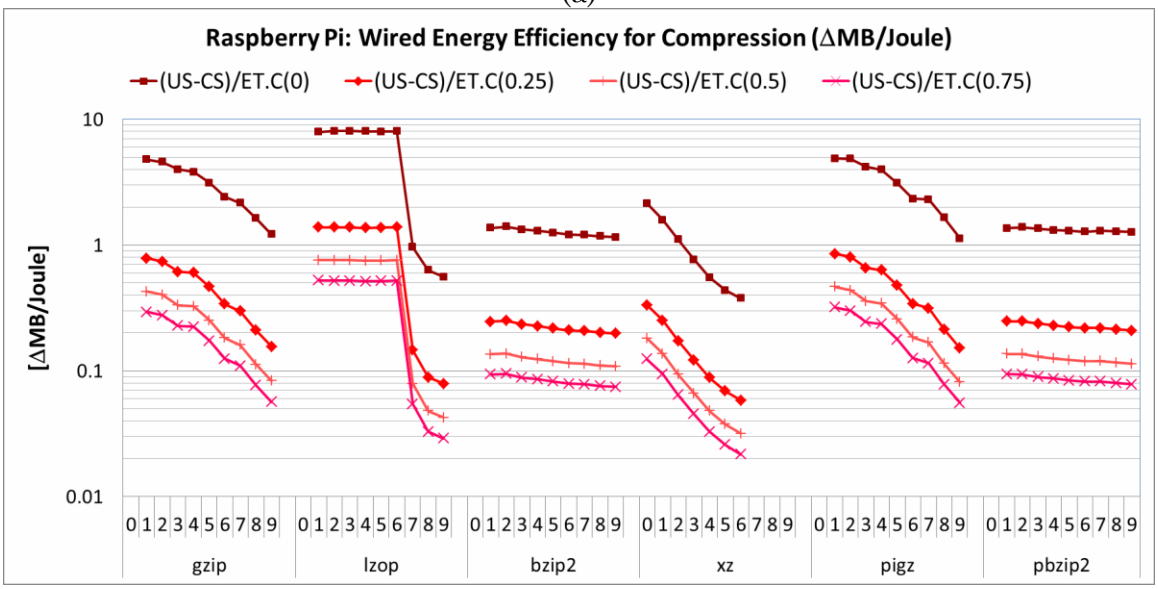
6.3.2 Wired

Figure 6.5 and Figure 6.6 show the energy efficiency for compression and decompression tasks for the Wired experiment reported in MB/J and in ΔMB/J as a function of the idle current. In addition, Figure 6.5(a) and Figure 6.6(a) show the energy efficiency for the uncompressed upload (US/ET.UUP) and uncompressed download (US/ET.UDW) as a function of the idle current. This way, one can easily identify cases when compression and decompression transfers offer higher energy efficiency than raw uploads (US/ET.C(I_{idle}) > US/UUP(I_{idle})) and raw downloads (US/ET.D(I_{idle}) > US/ET.UDW(I_{idle})). With ΔMB/J metric, on other hand, energy efficiency for raw network transfer cannot be reported.

The energy efficiency for compression is reported in Figure 6.5. When I_{idle}=0, gzip, pigz, and lzop with -1 to -6 and xz with -1 to -2 provide higher energy efficiency than the raw network upload. However, only lzop with -1 to -6 provides higher energy efficiency for all considered idle currents. The most energy efficiency utility is lzop with -1 to -6 achieving ~15.7 MB/J when I_{idle} = 0, ~ 2.7MB/J when I_{idle} = 0.25 A, and ~ 1.52 MB/J when I_{idle}= 0.5 A. bzip2, pbizp2, and xz exhibit rather low energy efficiency for compression. These observations hold when the alternative energy efficiency metric is considered.



(a)

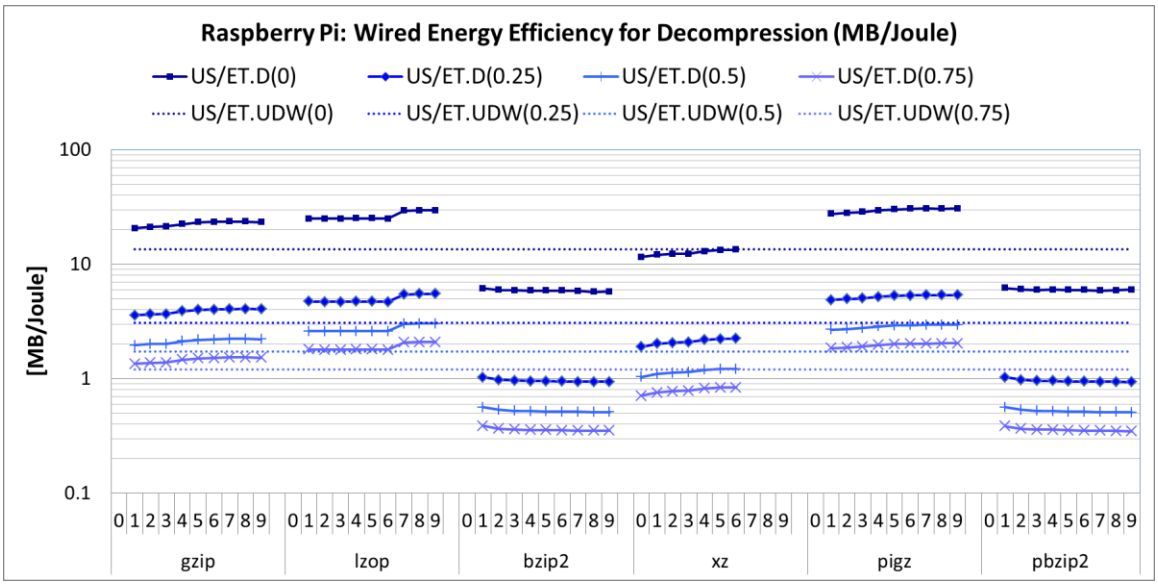


(b)

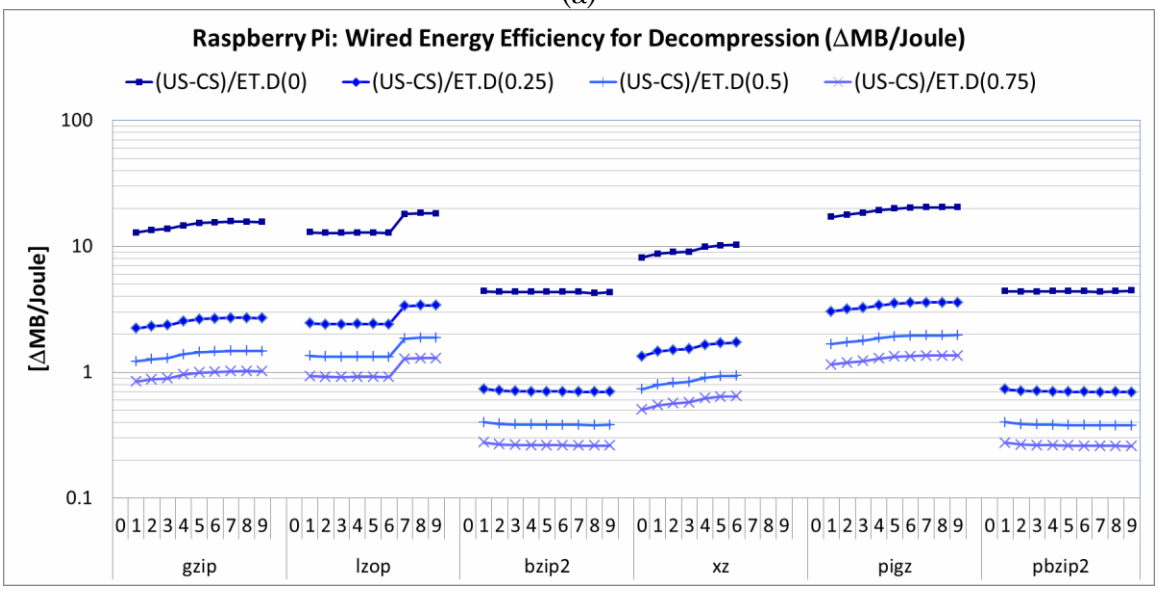
Figure 6.5 Raspberry Pi: Wired Energy Efficiency for Compression

The energy efficiency of decompression tasks using gzip, lzop, and pigz exceeds the energy efficiency of the uncompressed download for all considered idle currents, whereas bzip2, pbzip2, and xz are less energy efficient (Figure 6.6). The energy efficiency increases for higher compression levels (except for bzip2/pbzip2),

achieving ~29.6 MB/J for lzop, ~ 30.6 MB/J for pigz, and ~23.3 MB/J for gzip when I_{idle} = 0 A. Similarly to how it was noted before, on single-core Raspberry Pi, pigz outperforms its sequential counterpart (by ~33%). Both pigz and lzop emerge as the most energy-efficient utilities, outperforming gzip when I_{idle} = {0.25, 0.5, 0.75} A.



(a)



(b)

Figure 6.6 Raspberry Pi: Wired Energy Efficiency for Decompression

6.4 Conclusions

The experimental results for the Raspberry Pi platform show that the compression tasks should utilize the lowest compression levels, and that the decompres-

sion tasks should utilize the highest compression level (for exception of bzip2 and pbzip2) for both the throughput and energy efficiency.

Table 6.1 summarizes the throughput results. lzop performs the best for compression and decompression in the Local experiment and for compression in the Wired experiment. The best throughput for decompression in the Wired experiment is achieved by pigz, followed by lzop and gzip (pigz outperforms lzop by 3.9%). However, lzop is the only utility that effectively increases the network throughput for uploads in the Wired experiment.

Table 6.1 Throughputs on Raspberry Pi @ 700MHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
	Best Utility	*Th.C [MB/s]*	*Th.UUP [MB/s]*	*Best Utility*	*Th.D [MB/s]*	*Th.UDW [MB/s]*
LOCAL	lzop -1 to -6	9.5		lzop -1 to -9	26.4	
WIRED	lzop -1 to -6	4	3.6	pigz -8 to -9	8.45	4.97

Table 6.2 shows the energy efficiency. lzop is the most energy-efficient for both the Local and Wired experiment for compression and decompression (when $I_{idle} \neq 0$ A), while pigz is the most energy-efficient for the Wired experiment for decompression when $I_{idle} = 0$ A. In the Wired experiment, the most energy efficient compressed upload with lzop -1 achieves 15.7 MB/J, which ~10.26 times more energy-efficient than 1.53 MB/J achieved with the uncompressed upload (assuming Iidle = 0 A). The most energy-efficient decompressed download using pigz with -9 achieves

30.5 MB/J, which is ~2.25 times better than the uncompressed download that achieves 13.55 MB/J.

Table 6.2 Energy Efficiency on Raspberry Pi @ 700MHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
LOCAL	*Best Utility*	*EE.C [MB/J]*	*EE.UUP [MB/J]*	*Best Utility*	*EE.D [MB/J]*	*EE.UDW [MB/J]*
I_{idle} = 0 A	lzop -1 to -6	45		lzop -6 to -9	90	
I_{idle} = 0.25 A	lzop -1 to -6	6.5		lzop -6 to -9	17	
I_{idle} = 0.5 A	lzop -1 to -6	3.5		lzop -1 to -9	9.5	
WIRED						
I_{idle} = 0 A	lzop -1 to -6	15.7	1.53	pigz -6 to -9	30.5	13.55
I_{idle} = 0.25 A	lzop -1 to -6	2.7	1.00	lzop -7 to -9	5.5	3.07
I_{idle} = 0.5 A	lzop -1 to -6	1.5	0.74	lzop -7 to -9	3	1.73

Use of parallel compression utility such as pigz, even on a single core system, offers gains in the throughput and the energy efficiency for the compression and de-compression tasks. Table 6.3 summarizes the throughput and the energy efficiency gains of pigz and pbzip2 when compared to the sequential counterparts for all experimental cases.

Table 6.3 Performance Gain of Parallel Utilities on Raspberry Pi @ 700MHz

	I_{idle} (A)	Throughput Gain (compression/decompression)	
		Local	Wired
pigz		16.4%/69.5%	10.16%/33.5%
pbzip2		0%/0%	0%/0%
		Energy Efficiency Gain (compression/decompression)	
		Local	Wired
pigz	0.00	0%/53%	1.340%/31.52%
	0.25	13.25%/67.34%	7.936%/33.08%
	0.50	14.7%/68.03%	10.29%/33.48%
	0.75	15.0%/68.66%	8.51%/33.5%
pbzip2	0.00	0%/0%	0%/0%
	0.25	0%/0%	0%/0%
	0.50	0%/0%	0%/0%
	0.75	0%/0%	0%/0%

CHAPTER 7

WORKSTATION RESULTS

This chapter presents the results of the experimental evaluation for the workstation platform. Section 0 describes the compression ratio achieved by the compression utilities for all compression levels. Section 7.2 discusses the compression and decompression throughputs. Section 7.3 discusses energy efficiency of compression and decompression tasks. Section 7.4 discusses the effects of frequency scaling on processor cores. Section 7.5 summarizes findings from the workstation experiments.

7.1 Compression ratio

Figure 7.1 shows the compression ratio for the input dataset used on the workstation platform (totalInput.tar and enwik9.xml). It can be observed that compression values for totalInput.tar are identical to those for Pandaboard and Raspberry Pi shown in Figure 5.1 for the reason of using the same versions of compression and decompression utilities. The compression ratios between two dataset are almost identical for exception of xz -9 which reaches compression ratio of 4.68 for enwik9.xml dataset and 4.31 for totalInput.tar dataset. This exception can be explained by substantially larger size of enwik9.xml, which allows xz at highest levels to work with full compression potential. Because of insignificant differences in compression ratios between two datasets, enwik9.xml is used for the rest of this chapter for presenting the results.

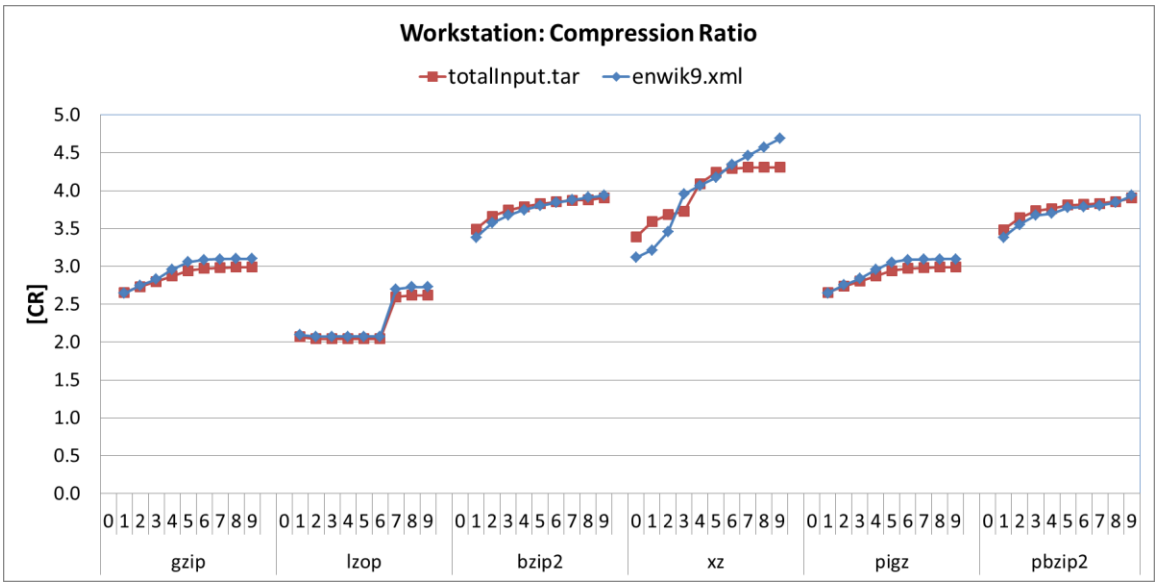


Figure 7.1 Workstation: Compression Ratio

7.2 Compression and Decompression Throughputs

7.2.1 Local

Figure 7.2 shows the overall compression and decompression throughput for the Local experiment on the workstation platform using enwik9.xml dataset. As seen in Chapters 5 and 6, the compression throughput in the Local experiment varies widely across different compression utilities as well as across different compression levels of a single compression utility. The higher compression levels result in slightly higher decompression throughputs, whereas lower compression levels result in higher compression throughputs.

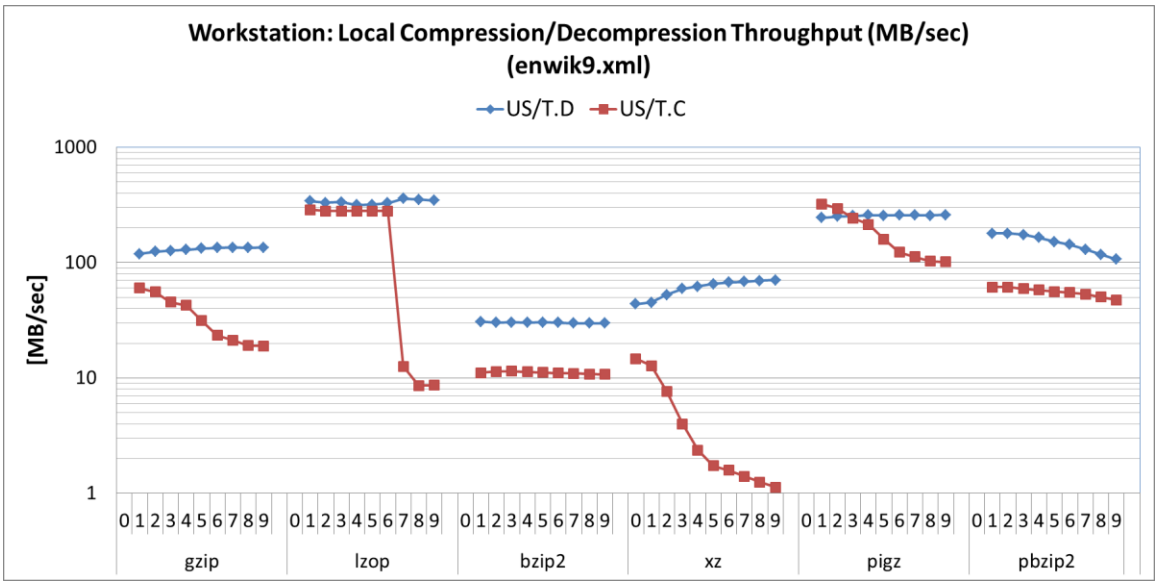


Figure 7.2 Workstation: Local Compression/Decompression Throughput (MB/sec) (enwik9.xml)

For compression, the highest throughput of 321.82 MB/sec is achieved by pigz -1 and followed by pigz -2 with 295.5 MB/sec. The higher compression levels of pigz drop to 160.5, 123.3, 112.2, 102.5 and 101.7 MB/sec. The third highest compression throughput of ~280 MB/sec (after pigz -1, -2) is achieved by lzop -1 to -6. However, the compression throughput for lzop drops dramatically for the highest compression levels (to 12.62, 8.62, and 8.61 MB/sec for -7, -8 and -9 respectively). Additionally, both pigz and pbzip2 outperform their sequential counterparts by a factor of ~5.35 for all compression levels. The pbzip2 utility has compression throughput ranging from 61.19 to 47.5 MB/sec, and the gzip utility has compression throughput ranging from 60.23 to 19.02 MB/sec. xz and bzip2 achieve significantly lower compression throughputs (e.g., from 14.66 to 1.13 MB/sec for xz and from 11.39 to 10.74 for

bzip2). xz slows down dramatically with increasing compression level to smallest compression throughput of 1.13 MB/sec with -9.

The decompression throughputs are much closer to the compression throughputs on the workstation platform than on Pandaboard or Raspberry Pi. As noted before, higher compression levels usually result in an increase of the decompression throughput due to typically smaller compressed files that require less time for input operations. bzip2 and pbzip2 are exceptions, since increased computational complexity of decompression outweighs the benefits of increased compression ratios. The highest decompression throughput of 358.97 MB/sec is achieved by lzop, followed by pigz (245.16 to 258.92 MB/sec) and gzip (119.11 to 135.02 MB/sec). The pigz and pbzip2 utilities offer improvements in decompression throughputs over their sequential counterparts.

7.2.2 Wired

Figure 7.3 shows the compression and decompression throughputs in the Wired experiment on the workstation platform for enwik9.xml dataset. The dashed lines represent the measured effective network throughput when the uncompressed input files are uploaded to the remote server US/T.UUP (10.71 MB/sec) and downloaded from the remote server US/T.UDW (10.72 MB/sec) over the wired Ethernet interface.

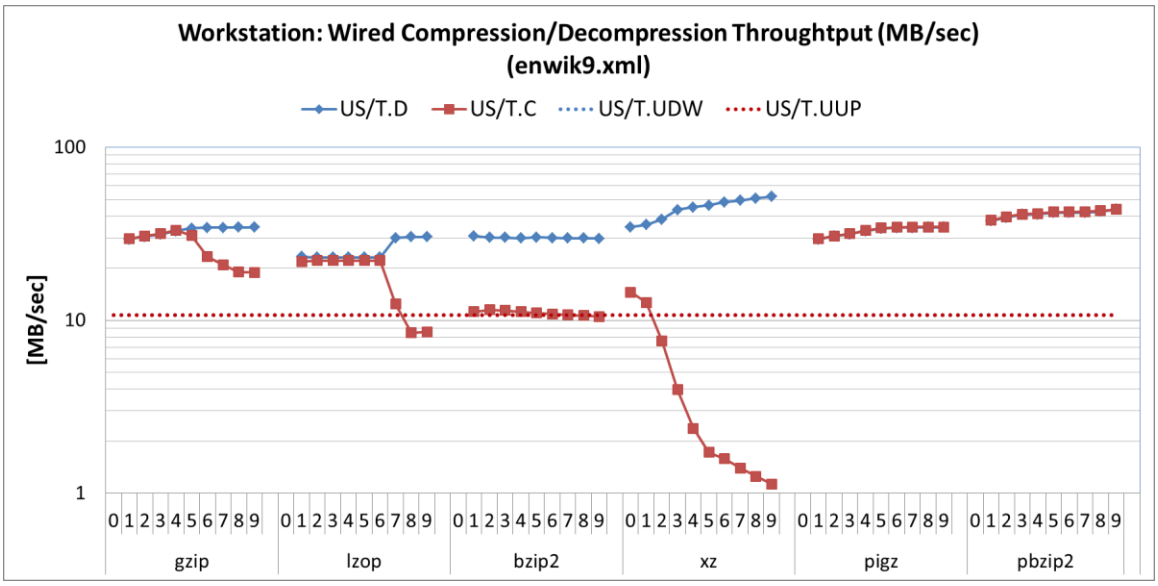


Figure 7.3 Workstation: Wired Compression/Decompression Throughput (enwik9.xml)

Similarly to results for the Wired experiment on Pandaboard and Raspberry Pi, the compression throughput is limited by the effective network throughput. Therefore, the compression throughput is always below the CR*(US/T.UUP). For example, in enwik9.xml, the compression throughput of gzip -1 to -4 goes up to ~30 to 33 MB/sec, which is very close to CR*10.71 MB/sec for each compression level (28.27 to 31.70 MB/sec). lzop -1 to -6 levels off at 21.84 MB/sec, which is slightly below 2.07*10.71 = 22.17 MB/sec (the compression ratio for lzop -1 is 2.07). The effective compression throughput is significantly lower for lzop (by a factor of ~13), pigz (by a factor of ~9) and gzip (by a factor of 2) in the Wired experiment than in the Local experiment.

The highest compression throughput of 43.72 and 37.07 MB/sec is achieved by pbzip2 -9 for enwik9.xml and totalInput.tar datasets respectively. Second highest

compression throughput is achieved by pigz (29.58 to 34.63 MB/sec). Third largest compression throughput is taken by gzip on the lower compression levels. In comparison with results from Pandaboard and Raspberry Pi, lzop comes in fourth for both dataset cases. The least effective compressions in throughput are bzip2 and xz.

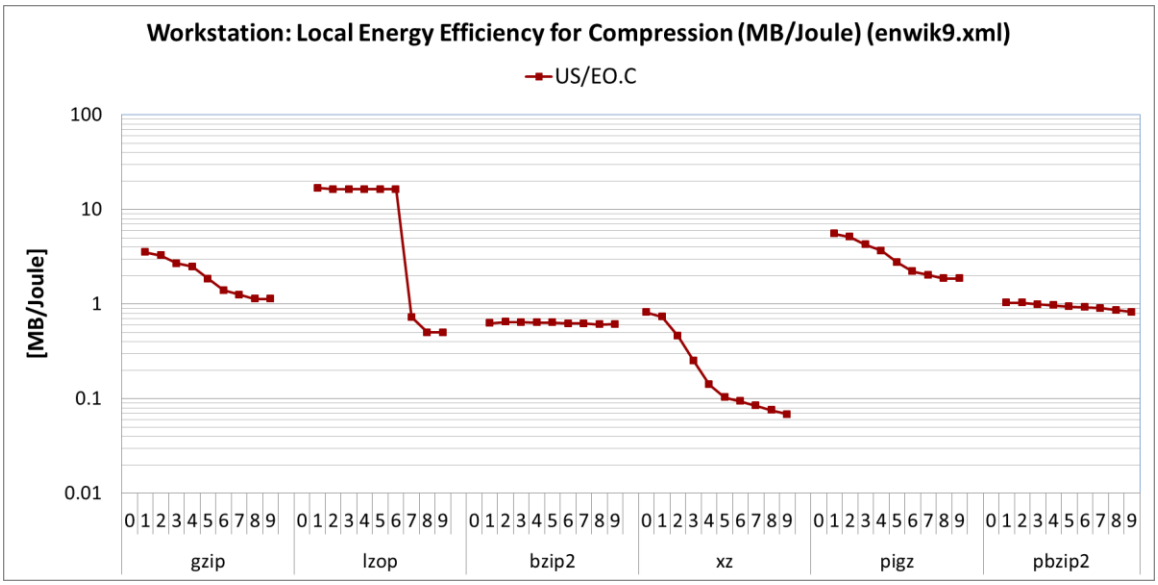
The same limit of the effective network throughput is imposed on the decompression tasks. Thus, the decompression throughput should be below CR*(US/T.UDW) for all utilities, which can be observed across all decompression utilities. Additionally, the effective decompression throughput is significantly lower for lzop (by a factor of ~14), pigz (by a factor of ~10) and gzip (by a factor of ~5.4) in the Wired experiment than in the Local experiment. The highest decompression throughput of 51.93 MB/sec is achieved by xz -9. The second highest decompression throughput is achieved by pbzip2 (37.80 to 43.72 MB/sec). The third largest compression throughput is taken by pigz and gzip with decompression throughput of ~29.5 to ~34.5 MB/sec.

7.3 Energy Efficiency

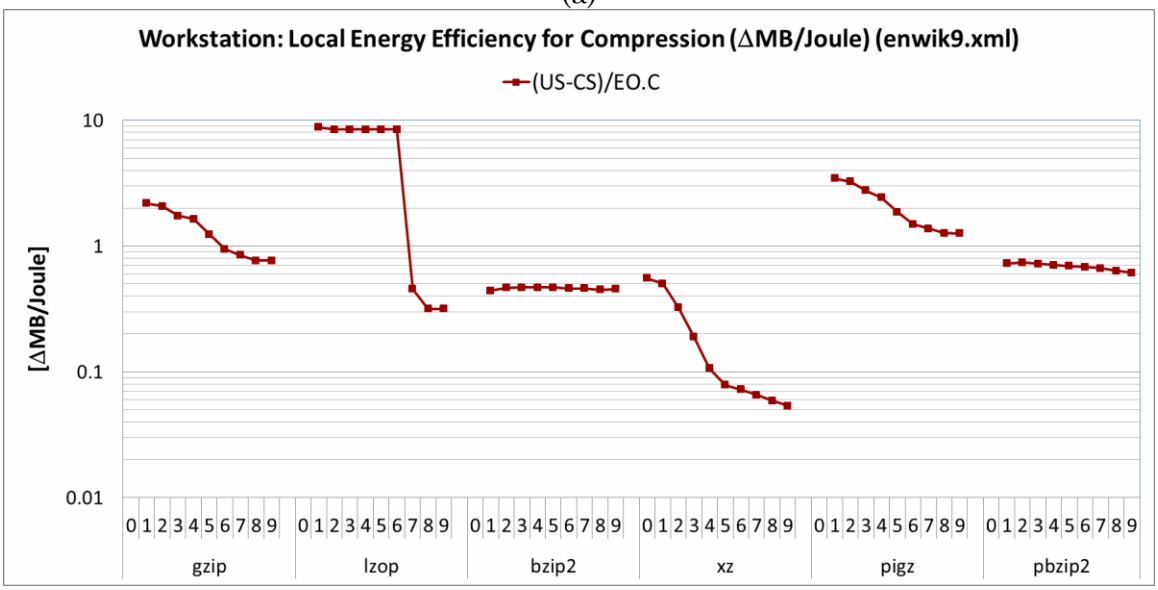
7.3.1 Local

Figure 7.4 and Figure 7.5 show the energy efficiency for compression and decompression tasks in the Local experiment reported in MB/J (US/EO.C and US/EO.D) and ΔMB/J (|US-CS|/EO.C and |US-CS|/EO.D). Because of differences in the experimental setup on the workstation, no idle current was used to report energy efficiency; instead the energy overhead reported by the likwid-powermeter tool is used to derive energy efficiency, which is equivalent to ET.C(0) and ET.D(0) metrics from Chapters 5 and 6.

The energy efficiency of compression tasks varies widely for different utilities and different compression levels as shown in Figure 7.4. The most energy efficient compression utility by far is lzop -1 to -6 with the energy efficiency of 16.8 MB/J. After lzop, pigz and gzip are following closely with the energy efficiencies ranging from 5.54 to 1.85 MB/J for pigz and from 3.51 to 1.13 MB/J for gzip. The pigz and pbzip2 have higher energy efficiency than their sequential counterparts. The least energy-efficient choices from six are pbzip2, bzip2 and xz.



(a)

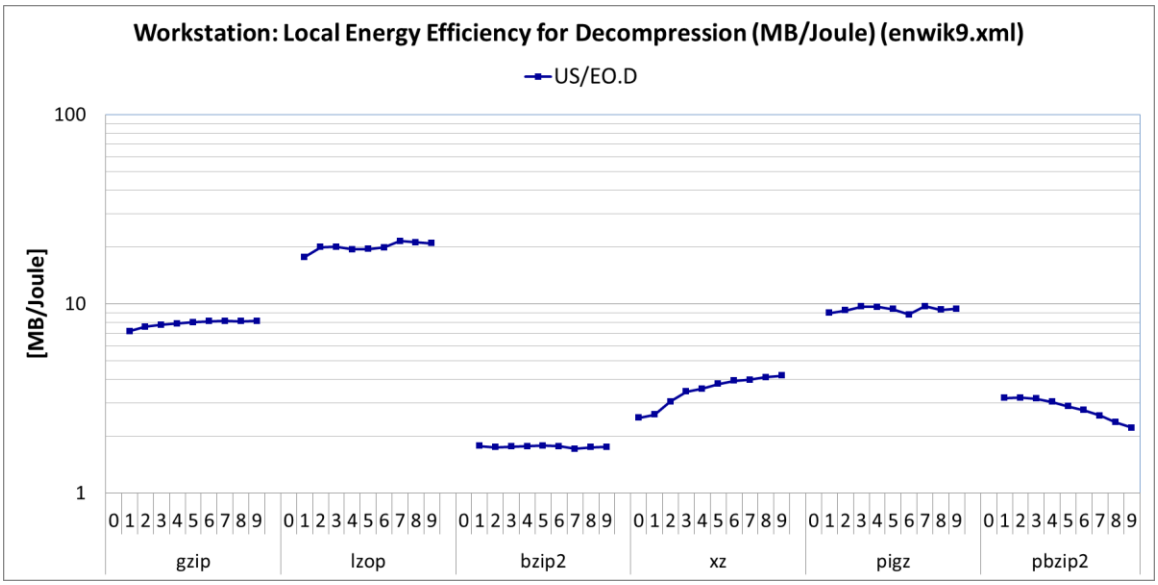


(b)

Figure 7.4 Workstation: Local Energy Efficiency for Compression (enwik9.xml)

The energy efficiencies of the decompression tasks vary widely for different utilities (Figure 7.5). The energy efficiency increases for higher compression levels for all utilities except bzip2 and pbizp2. The lzop utility, despite lower compression ratio, has the highest energy efficiency of 21.5 MB/J. Following lzop, pigz and gzip

come second and third having energy efficiency of 9.8 and 8.14 MB/J. Similarly to the compression results, the parallel utilities have better energy efficiency than their sequential counterparts on almost all compression levels. The least energy-efficient choices from six utilities are bzip2, pbzip2 and xz.



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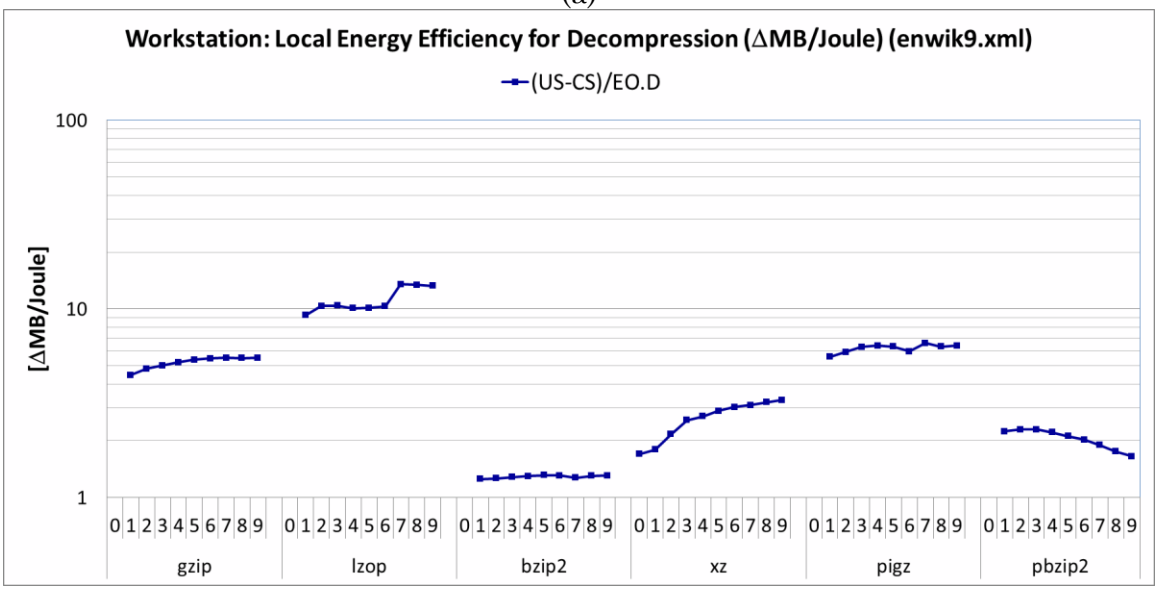


(b)

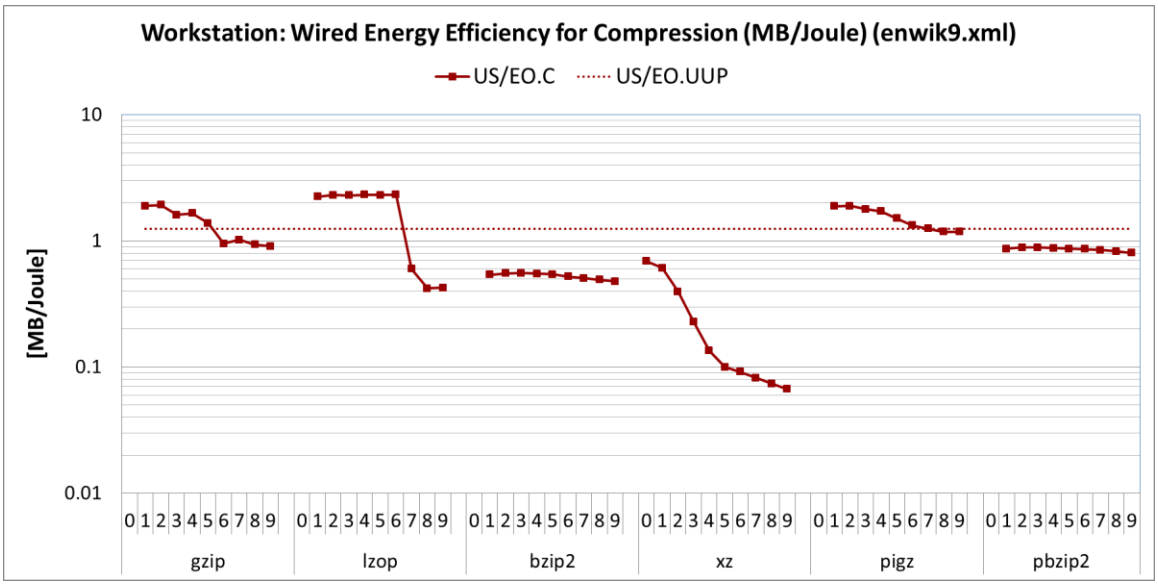
Figure 7.5 Workstation: Local Energy Efficiency for Decompression (enwik9.xml)

7.3.2 Wired

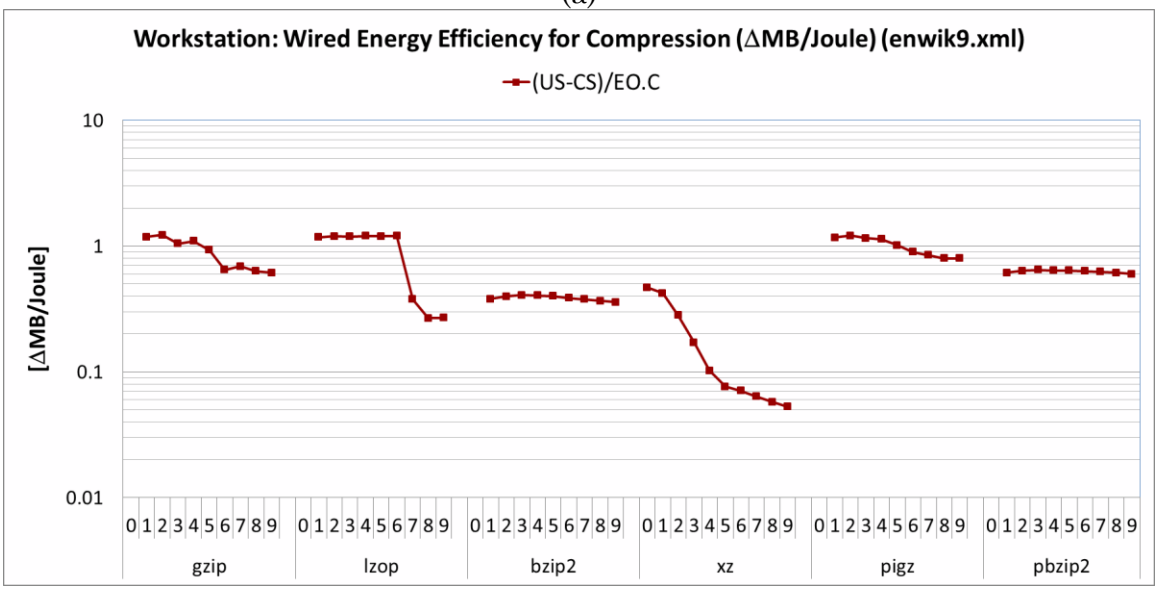
Figure 7.6 and Figure 7.7 show the energy efficiency for compression and decompression tasks for the Wired experiment reported in MB/J (US/EO.C and US/EO.D) and ΔMB/J (|US-CS|/EO.C and |US-CS|/EO.D). Figure 7.6(a) and Fig-

ure 7.7(a) show the energy efficiency of the compression and decompression utilities, respectively, as well as the energy efficiency of the uncompressed upload (US/EO.UUP) and the uncompressed download (US/EO.UDW) transfer with a dashed line.

The results for compression tasks show that only a subset of utilities effectively improves energy efficiency over the uncompressed upload transfers (Figure 7.6): gzip with -1 to -5, pigz with -1 to -5, and lzop with -1 to -6. The most energy efficient utility is lzop with -1 to -6 with ~2.32MB/J, gzip -1 follows with ~1.9 MB/J. For parallel compression utilities, pigz does not offer any energy efficiency benefit when compared to gzip, but pbzip2 is almost twice more energy efficient than bzip2. Nonetheless, bzip2, pbzip2 and xz exhibit low energy efficiency for all compression levels and effectively increase energy use over the uncompressed file upload.



(a)

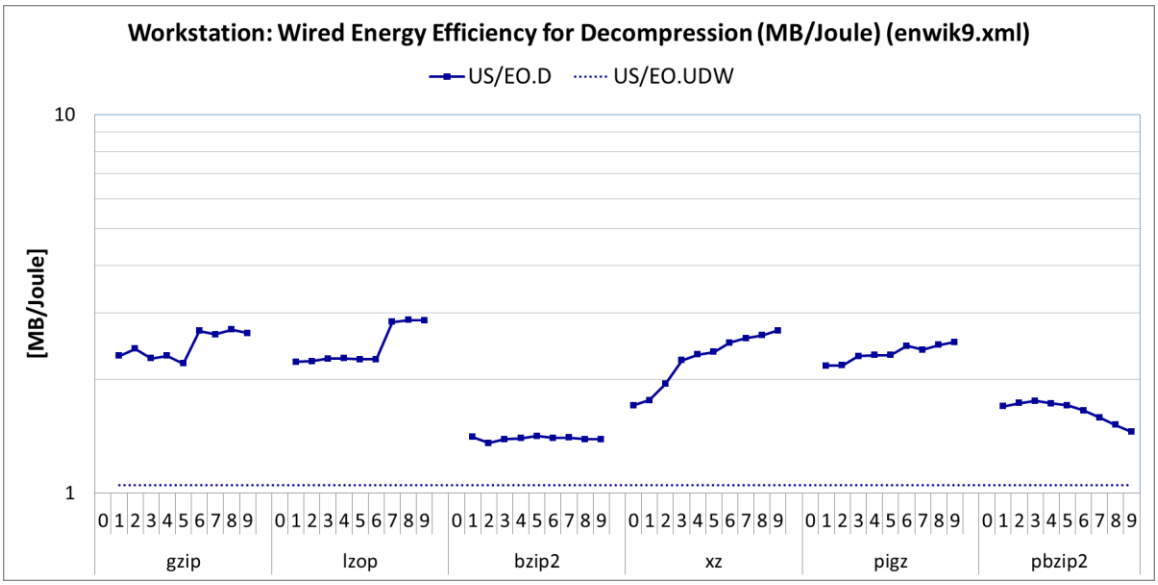


(b)

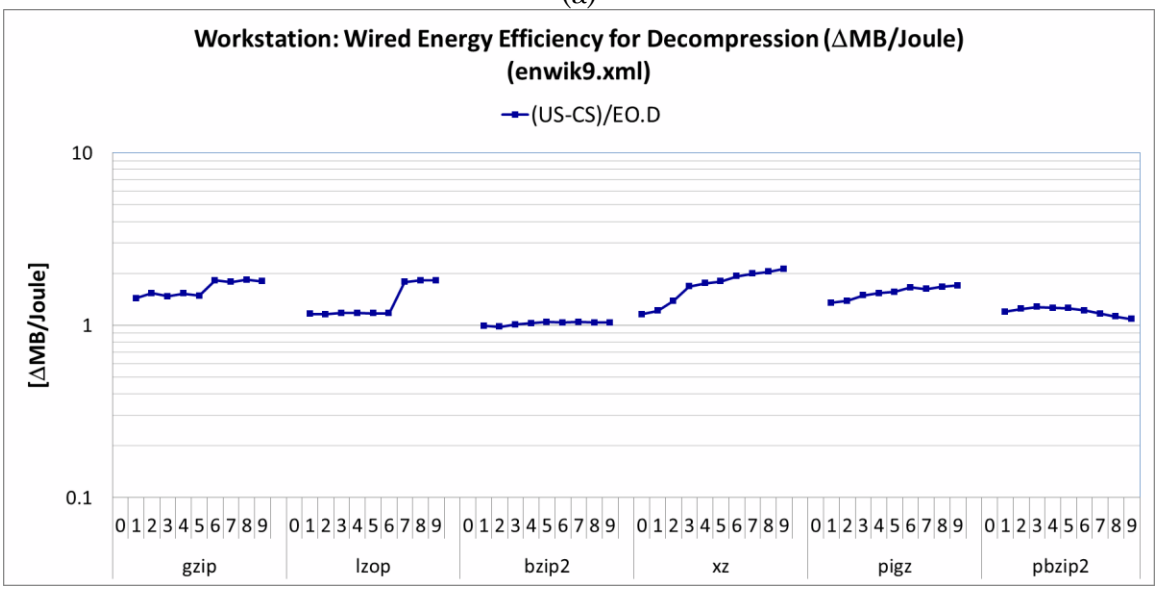
Figure 7.6 Workstation: Wired Energy Efficiency for Compression (enwik9.xml)

The energy efficiency of the decompression tasks exceeds the energy efficiency of the raw download for all utilities (Figure 7.7). The highest energy efficiency for decompression is achieved by lzop (2.86 MB/J). The second place is taken by xz with the highest compression levels (2.69 MB/J). The pigz and gzip utilities come in third

with decompression efficiency ranging from 2.17 to 2.51 MB/J for pigz and from 2.30 to 2.65 MB/J for gzip. Just as in compression, pigz does not have any benefit in energy efficiency over its sequential counterpart. The least energy efficient are pbzip2 and bzip2, but parallel utility outperforms its sequential counterpart by 20% on low compression levels (with 1.69 to 1.45 MB/J for pbzip2 and 1.40 to 1.39 MB/J for bzip2). Similarly to compression, ΔMB/J metric does not change relative distribution of the decompression results.



(a)



(b)

Figure 7.7 Workstation: Wired Energy Efficiency for Decompression (MB/Joule) (enwik9.xml)

7.4 Frequency scaling

The frequency scaling for the workstation platform covers frequency steps from 1.60GHz to 3.40GHz with 0.20GHz iteration step (highest of which is used to

describe and report results for Section 7.2 and Section 7.3). Similarly to Pandaboard, a complete set of all tasks is repeated from those sections above for each frequency step. Section 7.4.1 and Section 7.4.2 describe the effect of frequency scaling based on throughput and energy efficiency metrics for the Local and Wired experiments.

7.4.1 Local

7.4.1.1 Compression and Decompression Throughputs

Figure 7.8 and Figure 7.9 show the compression and decompression throughput on the Local experiment. The results confirm expectations that a higher clock frequency means a higher compression and decompression throughput.

The highest compression throughput across all frequencies is achieved by pigz -1, achieving 321.82 MB/sec on 3.40GHz and 151.37 MB/sec on 1.60GHz (Figure 7.8). Following pigz, lzop and pbzip2 come in second and third.

The highest decompression throughput across all frequencies is achieved by lzop -7 to -9, achieving ~350 MB/sec on 3.40GHz and ~168 MB/sec on 1.60GHz (Figure 7.9). Following lzop, pigz and pbzip2 come in second and third.

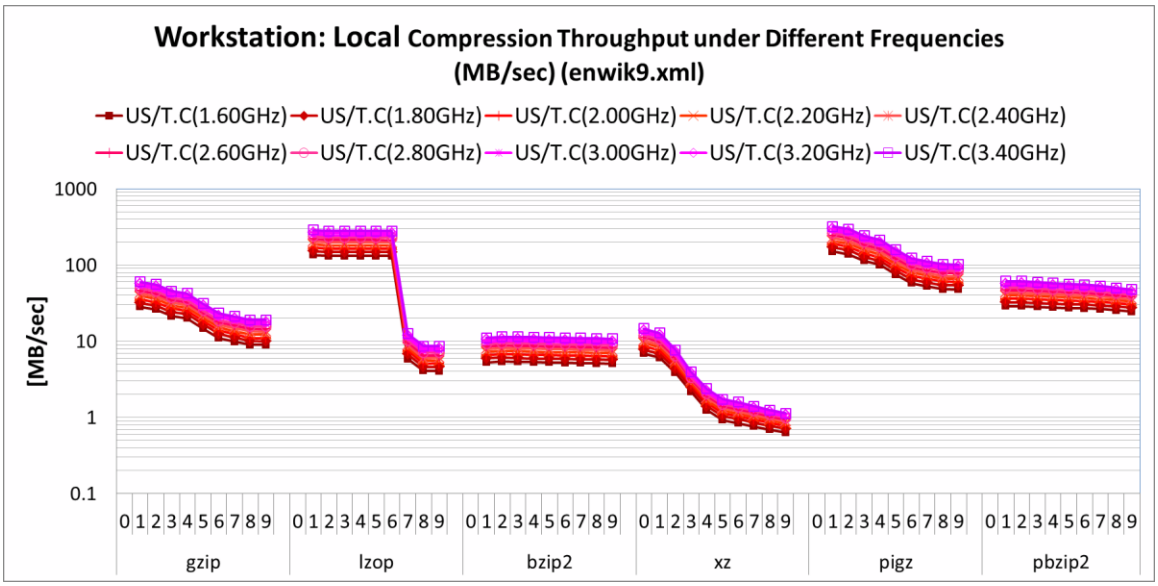


Figure 7.8 Workstation: Local Compression Throughput under Different Frequencies (MB/sec) (enwik9.xml)

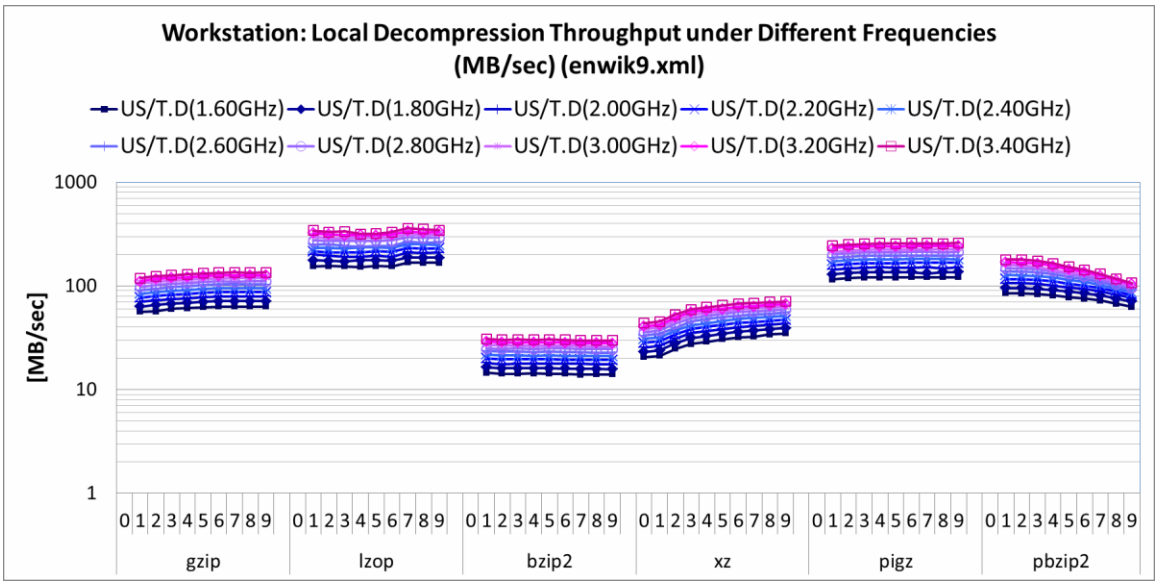


Figure 7.9 Workstation: Local Decompression Throughput under Different Frequencies (MB/sec) (enwik9.xml)

Figure 7.10 and Figure 7.11 show a comparison between the throughput ratios and the frequency ratios for compression and decompression in the Local experiment. The throughput ratio is derived by dividing the throughput of the highest frequency by the throughput of the current clock frequency (1.60GHz to 3.20GHz). The frequency ratio is derived by dividing the highest frequency by the corresponding current frequency (1.60GHz to 3.20GHz).

For compression, Figure 7.10, the gzip, lzop, bzip2 and pigz utilities have nearly identical the throughput ratios as their corresponding frequency ratios, indicating linear relationship between the frequency and the throughput. The only exceptions are xz and pbzip2 that have lower throughput ratios than corresponding frequency ratios for higher compression levels (highest with 3.40GHz/1.60GHz case), indicating a non-linear throughput change with frequency scaling on higher compression levels. For example, the compression throughput of xz with -9 when running at 1.6 GHz drops less than 1.5 times relative its throughput when running at 3.4 GHz, whereas the frequency ratio drops for more than 2.1 times.

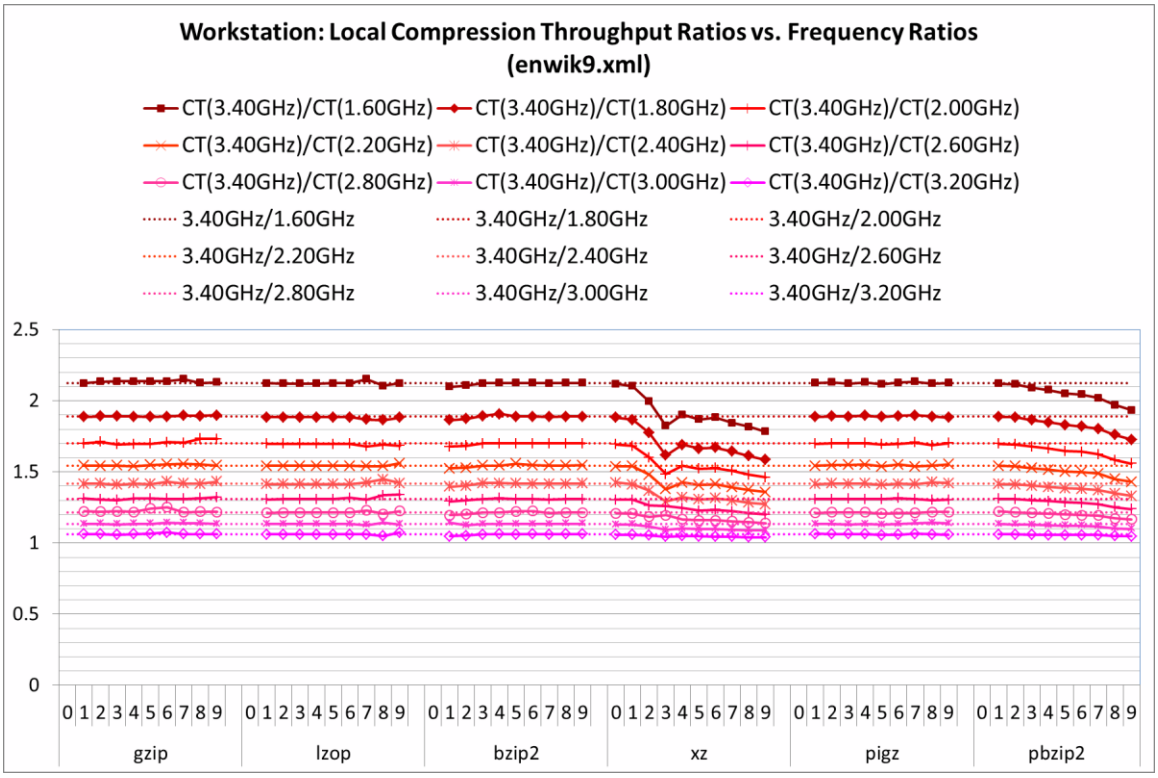


Figure 7.10 Workstation: Local Compression Throughput Ratios vs. Frequency Ratios (enwik9.xml)

Similar observations can be made for the decompression utilities as shown in Figure 7.11. The utilities such as gzip, lzop, bzip2, xz and pigz have the same or almost identical throughput ratio as their corresponding frequency ratios, indicating linear relationship between the frequency and throughput. An exception is pbzip2 that has lower throughput ratio than the corresponding frequency ratio for higher compression levels (highest with 3.40GHz/1.60GHz case).

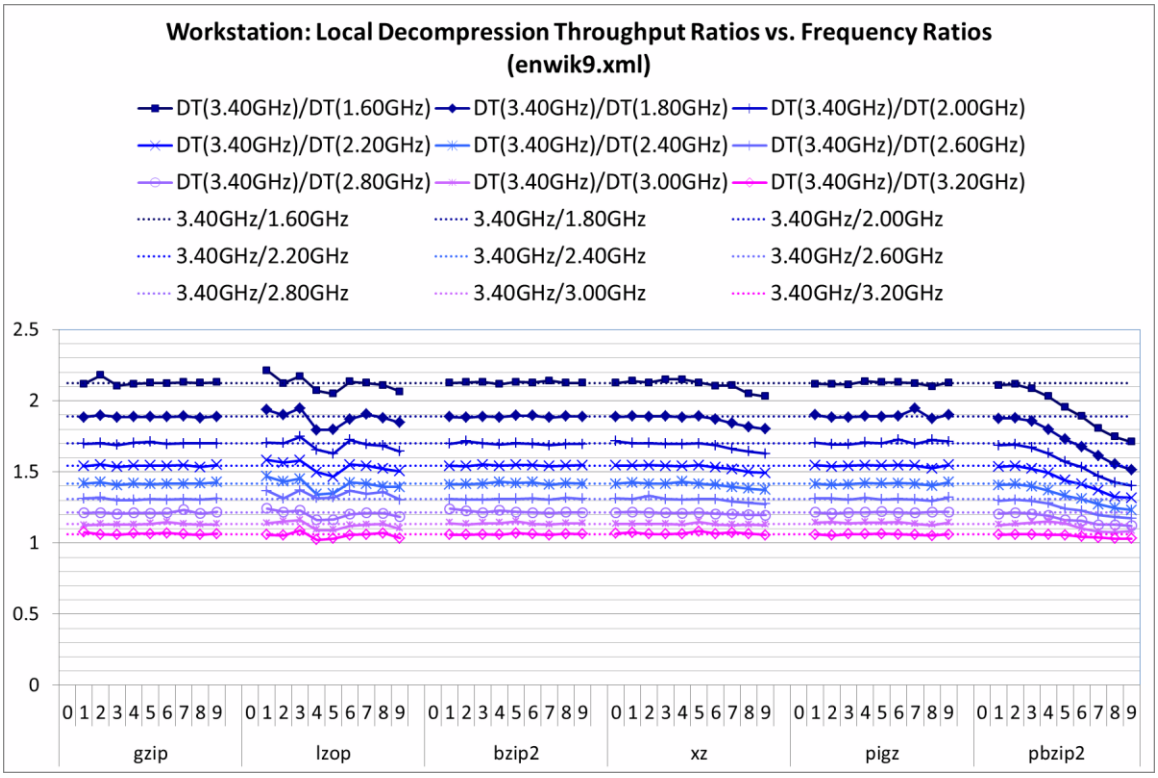


Figure 7.11 Workstation: Local Decompression Throughput Ratios vs. Frequency Ratios (enwik9.xml)

7.4.1.2 Energy Efficiency

Figure 7.12 and Figure 7.13 show the compression and decompression energy efficiency on the Local experiment.

The results shown in Figure 7.12 indicate that frequency scaling does not provide significant changes in the energy efficiency of compression tasks for the majority of utilities. The highest energy efficiency is achieved by lzop -1 across all frequencies, achieving ~17 MB/Joule.

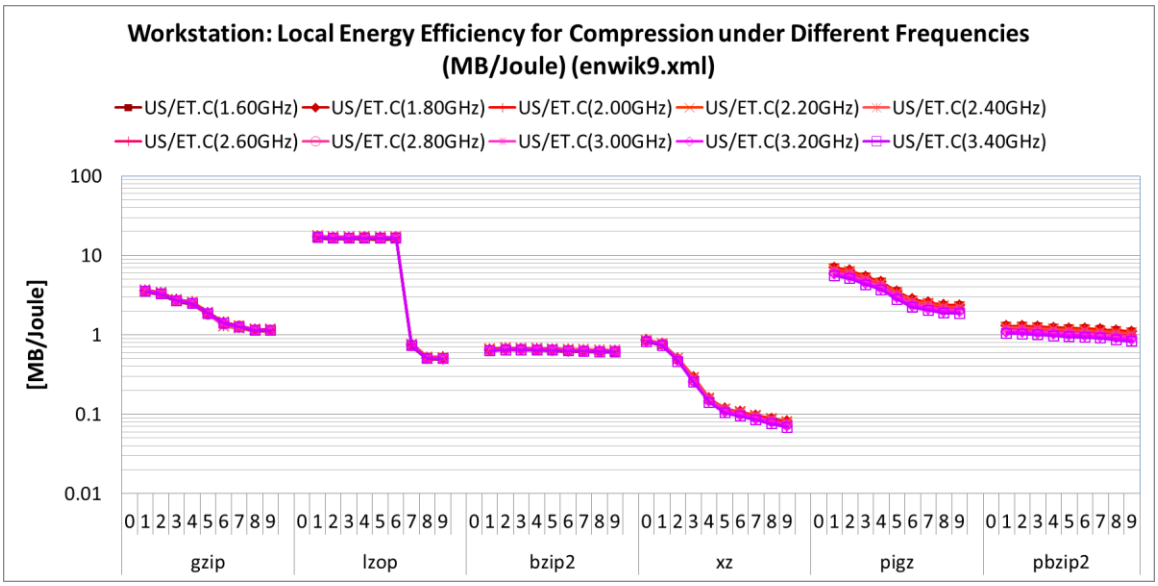


Figure 7.12 Workstation: Local Energy Efficiency for Compression under Different Frequencies (MB/Joule) (enwik9.xml)

The results shown in Figure 7.13 indicate that frequency scaling does not provide significant change in the energy efficiency of decompression tasks for the majority of utilities except for pigz and pbzip2. However, the highest energy efficiency is achieved by lzop -1 across all frequencies, achieving ~20 MB/Joule.

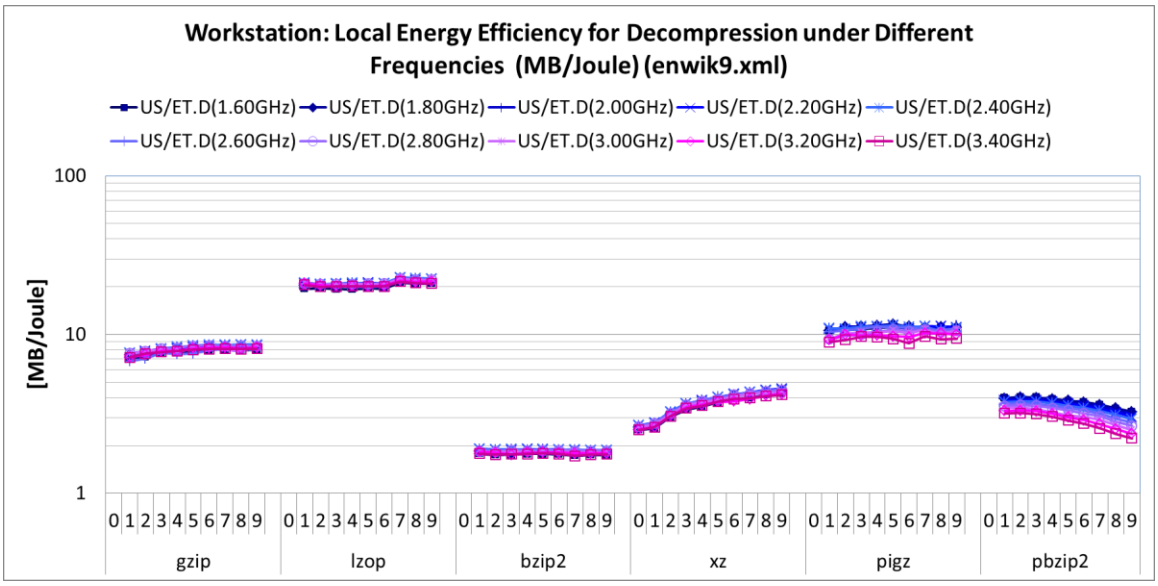


Figure 7.13 Workstation: Local Energy Efficiency for Decompression under Different Frequencies (MB/Joule) (enwik9.xml)

7.4.2 Wired

7.4.2.1 Compression and Decompression Throughputs

Figure 7.14 and Figure 7.15 show the compression and decompression throughput in the Wired experiment while varying the processor clock frequency.

The highest compression throughput is achieved by pbzip2 with -9, 43.73 MB/sec at the highest clock frequency of 3.40GHz (Figure 7.14). The highest throughput when processor is running at the lowest frequency of 1.6 GHz is achieved by gzip -1, 27.70 MB/sec. The compression utilities that do not see a substantial change in the compression throughput with a change in frequency are lzop -1 to -6 and pigz. The throughput of raw file upload benefits insignificantly with an increase in the processor clock frequency.

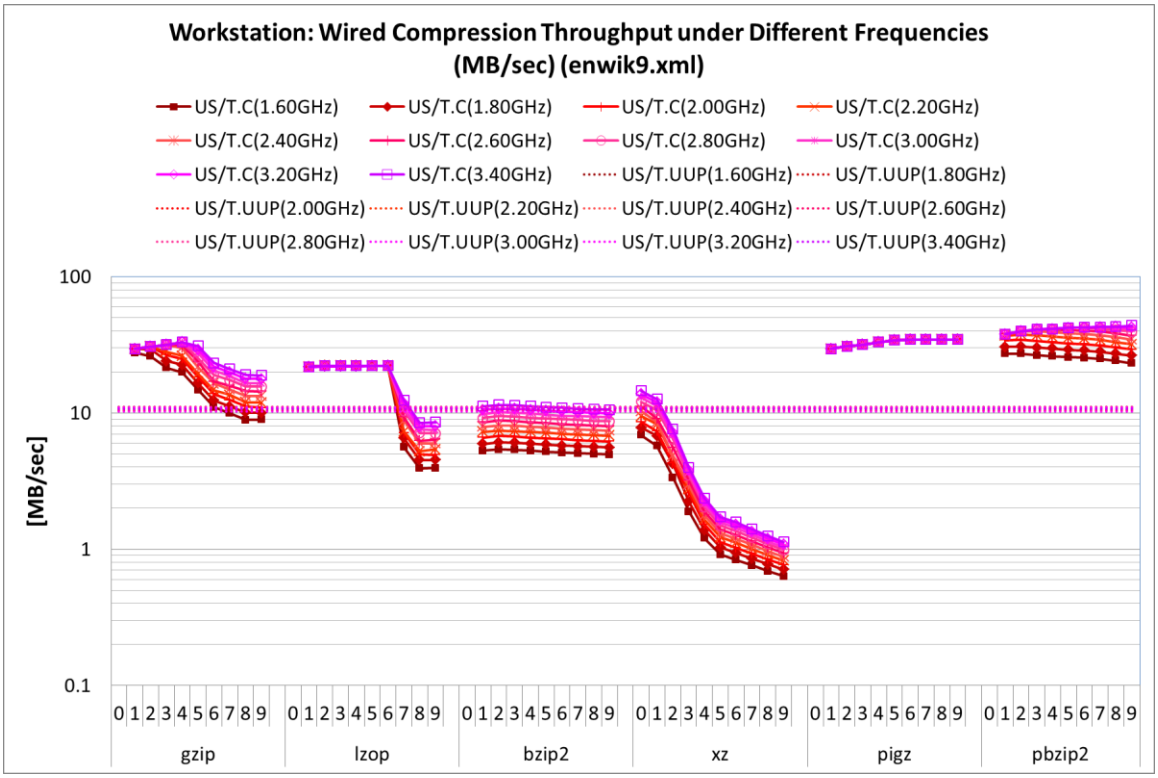


Figure 7.14 Workstation: Wired Compression Throughput under Different Frequencies (MB/sec) (enwik9.xml)

Figure 7.15 shows the decompression throughput while varying the processor clock frequency. The results indicate that the majority of decompression utilities (gzip, lzop, pigz, and pbzip2) do not see a substantial change in the throughput with a change in the processor clock frequency. Notable exceptions are xz and bzip2 that benefit from higher clock frequencies due to their high computational complexity. The throughput of the uncompressed file transfer benefits insignificantly from an increase in the clock frequency. The maximum decompression throughput is achieved by xz -9, 51.93 MB/sec at 3.40GHz. The highest throughput at the lowest frequency is achieved by pbzip2 -9, ~42 MB/sec at 1.60GHz.

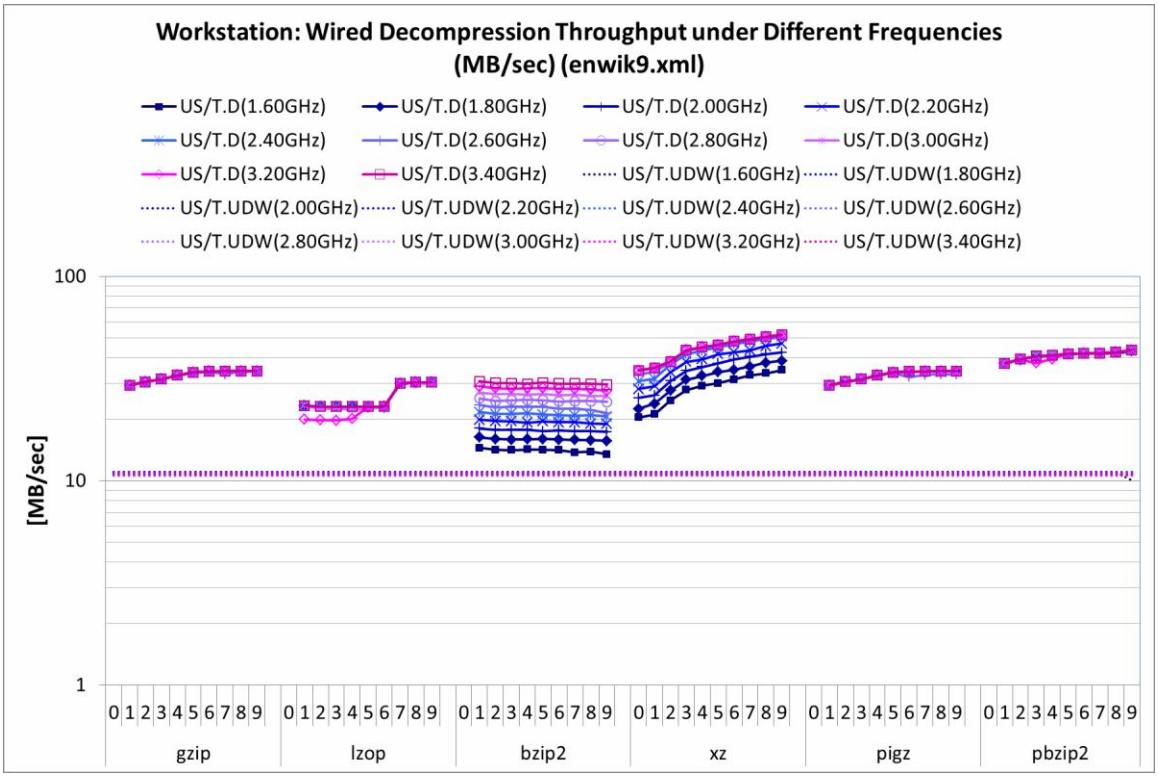


Figure 7.15 Workstation: Wired Decompression Throughput under Different Frequencies (MB/sec) (enwik9.xml)

Figure 7.16 and Figure 7.17 show the correlation between the throughput ratios and the frequency ratios for the compression and decompression tasks in the Wired experiment.

Unlike in the Local experiment, in the Wired experiment the throughput ratio versus the frequency ratio distribution changes widely as illustrated in Figure 7.16. Now only bzip2 and to a certain extent xz exhibit scalable behavior – the throughput ratios correspond to the frequency ratios. For the remaining utilities only highest compression levels show scalability. This can be explained as follows. The compression throughput even with a low processor clock frequency is higher than the achievable network throughput. This way, even if the processor is running at a

lower clock frequency, the network bandwidth is still going to be a limiting factor rather than the computational time. bzip2 and xz with high computational complexity have the compression throughput that is below the achievable network throughput, so they benefit from higher processor clock frequencies.

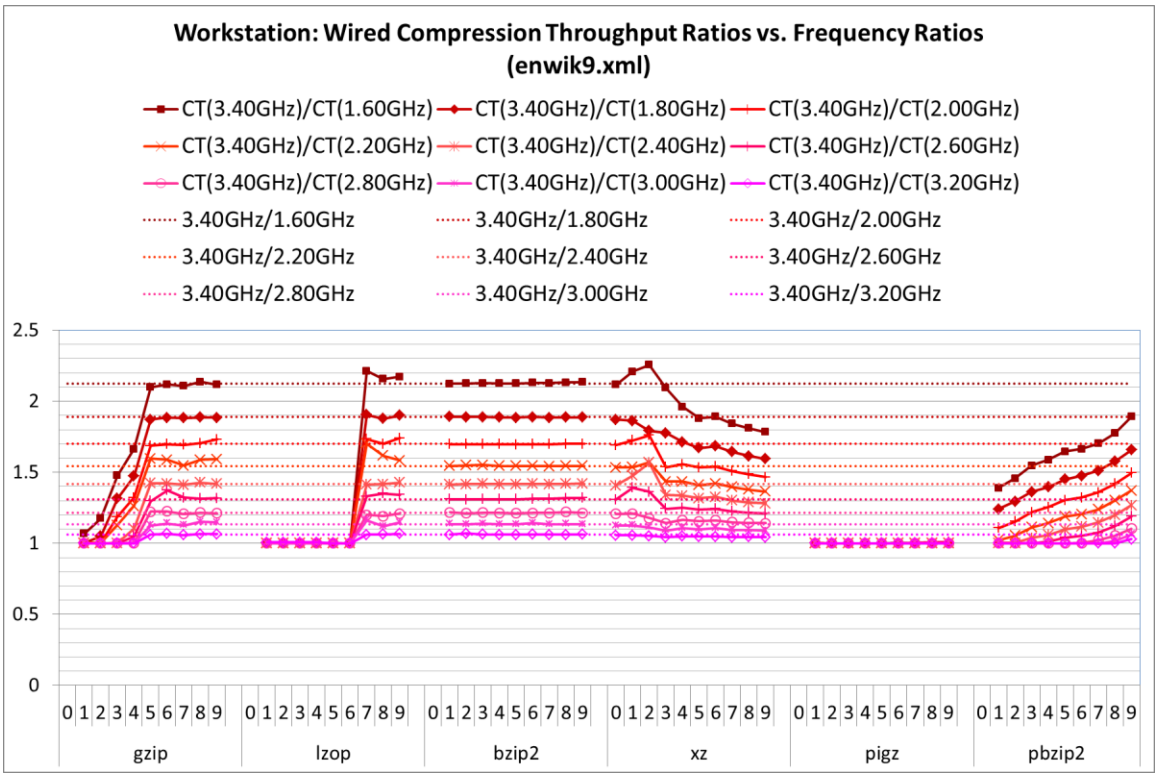


Figure 7.16 Workstation: Wired Compression Throughput Ratios vs. Frequencies Ratios (enwik9.xml)

Similar observations can be made for the decompression tasks as shown in Figure 7.17. For the majority of decompression tasks, the decompression throughput is far greater than the network throughput during uncompressed file downloads, regardless of the processor clock frequency. Consequently, by lowering the processor

clock frequency the effective decompression throughput remains unchanged. Exceptions are bzip2 and xz due to their high computational complexity.

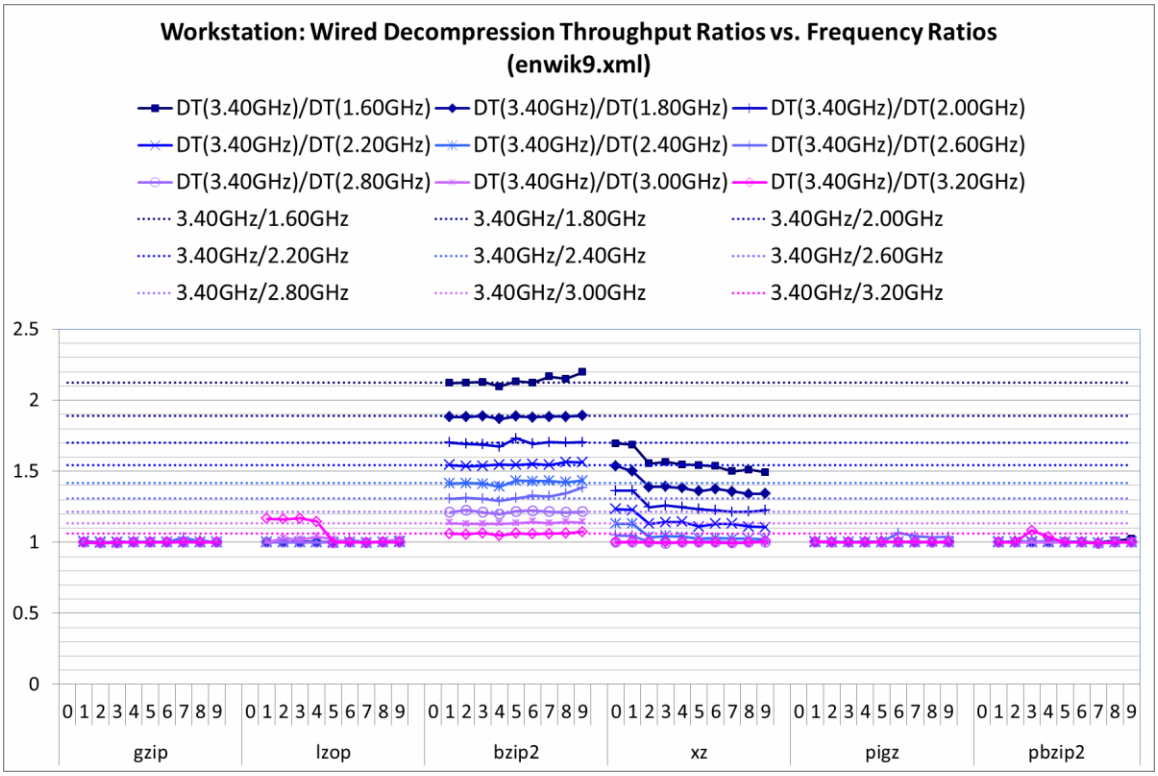


Figure 7.17 Workstation: Wired Decompression Throughput Ratios vs. Frequency Ratios (enwik9.xml)

7.4.2.2 Energy Efficiency

Figure 7.18 and Figure 7.19 show the compression and decompression energy efficiency in the Wired experiment.

The results in Figure 7.18 indicate that the energy-efficiency of the compression tasks increases as the clock frequency decreases. Thus, the lowest frequency 1.6 GHz is the most energy efficient choice across all compression utilities. The highest

energy efficiency is achieved by lzop across all frequency levels, ranging from ~2.9 MB/Joule at 1.60GHz to ~2.3 MB/Joule on 3.40GHz. The energy efficiency of the uncompressed file upload is highest at the clock frequency of 1.60 GHz.

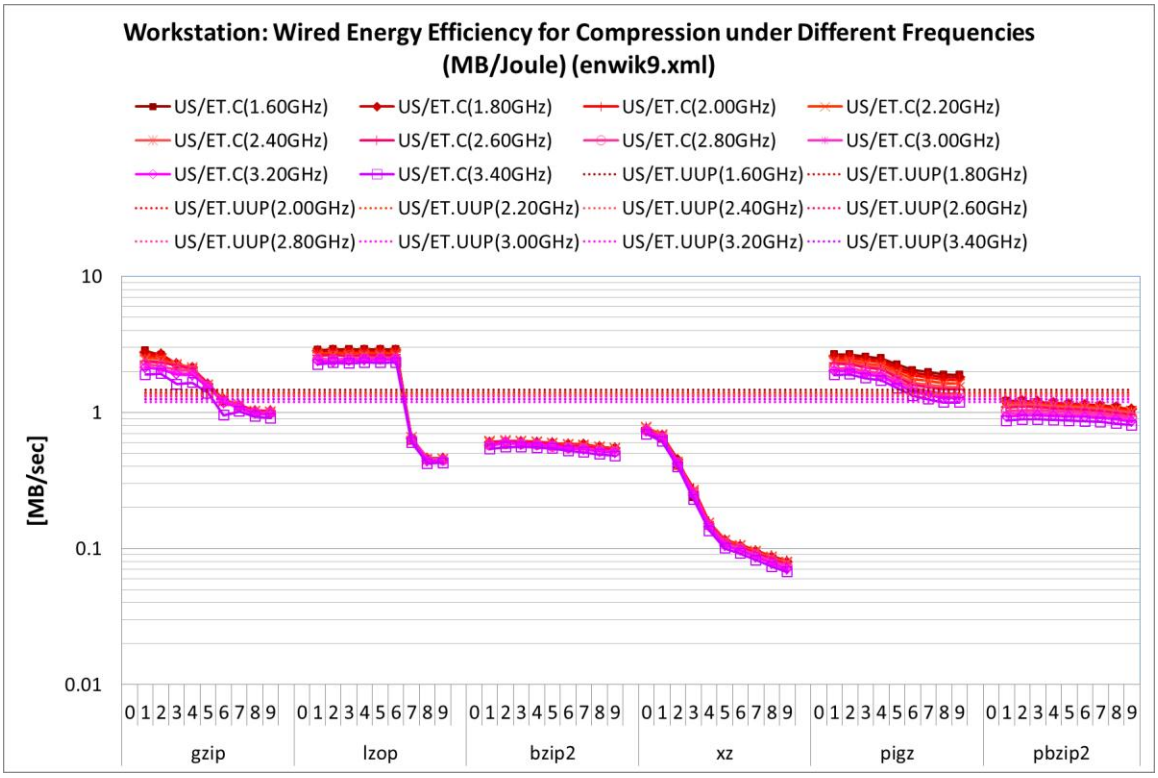


Figure 7.18 Workstation: Wired Energy Efficiency for Compression under Different Frequencies (MB/Joule) (enwik9.xml)

The results in Figure 7.19 indicate that the decompression energy efficiency increases as the clock frequency decreases for all decompression utilities. The highest decompression energy efficiency is achieved by lzop across all frequency levels, ranging from 3.97 MB/Joule at 1.60 GHz to 2.87 MB/Joule at 3.40 GHz. The energy

efficiency of the uncompressed file download also peaks for the lowest processor clock frequency.

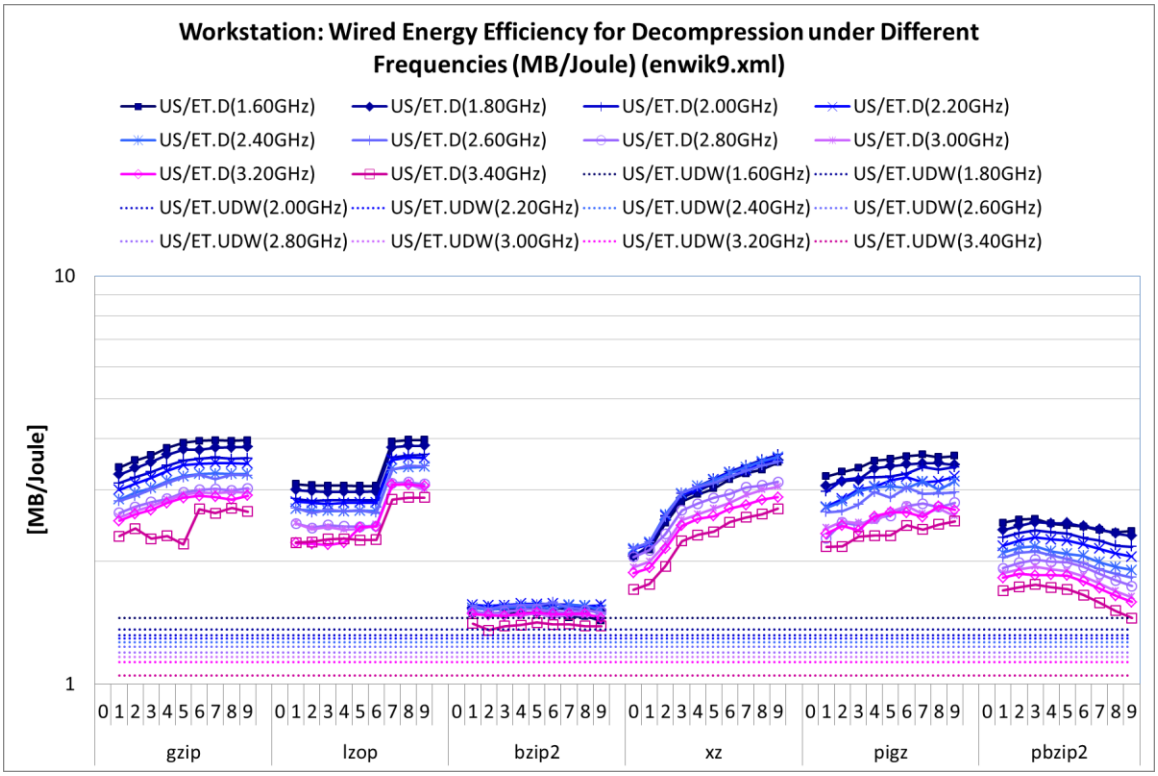


Figure 7.19 Workstation: Wired Energy Efficiency for Decompression under Different Frequencies (MB/Joule) (enwik9.xml)

7.5 Conclusions

The experimental results for the workstation platform show that compression tasks should utilize the lowest compression level to maximize throughput and energy efficiency, whereas decompression tasks should utilize the highest levels. A notable exceptions are bzip2 and pbzip2 where the computational complexity outweighs the benefits of increased compression ratios.

Table 7.1 summarizes the compression and decompression throughput results. pigz and lzop perform the best for compression and decompression in the Local experiment respectively. The best throughputs in the Wired experiment are achieved by pbzip2 and xz for compression and decompression respectively.

Table 7.1 Throughputs on Workstation @ 3.40GHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
	Best Utility	*Th.C [MB/s]*	*Th.UUP [MB/s]*	*Best Utility*	*Th.D [MB/s]*	*Th.UDW [MB/s]*
LOCAL	pigz -1	321.82		lzop -7	358.97	
WIRED	pbzip2 -9	43.73	10.71	xz -9	51.93	10.72

Table 7.2 summarizes the compression and decompression energy efficiency. The results indicate that compressed transfers could reduce the energy consumed relative to the uncompressed transfers. lzop is the most energy-efficient for both the Local and Wired experiment for compression and decompression. In the Wired experiment, the most energy efficient compressed upload with lzop -1 achieves 2.3 MB/J, which ~1.84 times more energy-efficient than 1.25 MB/J achieved with the uncompressed upload. The most energy-efficient decompressed download using lzop with -9 achieves 2.86 MB/J, which is ~2.72 times better than the uncompressed download that achieves 1.05 MB/J.

Table 7.2 Energy Efficiency on Workstation @ 3.40GHz

Experiment	Compression		Raw (UUP)	Decompression		Raw (UDW)
LOCAL	*Best Utility*	*EE.C [MB/J]*	*EE.UUP [MB/J]*	*Best Utility*	*EE.D [MB/J]*	*EE.UDW [MB/J]*
I_{idle} = 0 A	lzop -1 to -6	8.6		lzop -7 to -9	13.4	
WIRED						
I_{idle} = 0 A	lzop -1 to -6	2.3	1.25	lzop -7 to -9	2.86	1.05

The use of parallel compression utilities such as pigz and pbzip2 offers gains in the throughput and the energy efficiency for the compression and decompression tasks relative to their sequential counterparts. Table 7.3 summarizes the throughput and the energy efficiency gains of pigz and pbzip2 when compared to the sequential counterparts for all experimental cases.

Table 7.3 Performance Gains of Parallel Utilities on Workstation @ 3.40GHz

	I_{idle} (A)	Throughput Gain (compression/decompression)	
		Local	Wired
pigz		~80%	38.19%/3.67%
pbzip2		~80%	77.98%/53.20%
		Energy Efficiency Gain (compression/decompression)	
		Local	Wired
pigz	0.00	0%/9.9%	0%/0%
	0.25	32.86%/52.2%	13.91%/9.9%
	0.50	48.38%/62.78%	22.06%/9.20%
	0.75	56.64%/67.65%	25.56%/8.6%
pbzip2	0.00	0%/0%	0%/0%
	0.25	27.5%/34.49%	37.5%/28.7%
	0.50	43.5%/50.99%	58.13%/37.4%
	0.75	54.05%/58.82%	64.51%/41.26%

The frequency scaling analysis indicates that the compression and decompression throughputs suffer from lower frequency, which can be explained easily by the general observation that the execution time of each utility goes up with lowering of frequency. The energy efficiency increases when the clock frequency goes down for the selected utilities in the Local (factor of ~1.1 for pigz and pbzip2) and the Wired experiment (by factor of ~1.4 for all except pbzip2).

CHAPTER 8

CONCLUSIONS

This thesis describes an experimental evaluation of recent implementations of common compression utilities on three selected platforms, Pandaboard, a state-of-the-art mobile development platform, Raspberry Pi, a low-end mobile computer platform, and a workstation computer platform. The evaluation includes measurements of compression and decompression times and the total and overhead energies consumed by compression and decompression tasks. Metrics, such as compression ratio, compression/decompression throughput, and compression/decompression energy efficiency, are reported for all compression levels and platforms. Based on the results of this thesis, practical guidelines for selecting the most energy-efficient utilities are provided depending on the usage scenario. Across all systems and experiments, a single utility that always performs above network transfer for both throughput and energy efficiency is lzop. The lzop utility outperforms network transfer even on Raspberry Pi were all other compression utilities fail. Additionally, lzop outperforms network transfer for both throughput and energy efficiency when considering all I_{idle} currents for both Pandaboard and Raspberry Pi. Even that utilities such as pigz, gzip or xz outperform lzop, specifically for decompression on the slowest network throughput (on the Wireless experiment), they often fail to outperform network transfer in either throughput or energy efficiency in selected cases. Thus, if there is a need for one uniform utility that can perform well for both throughput and energy efficiency across different platforms and different network speeds, lzop provides this

by demonstrating that it can work well and never fail any of the experiments conducted across all evaluation hardware platforms of diverse hardware complexity and performance. Additional observations, from all experiments conducted in this thesis, indicate that it is always better to use the lowest compression level for compression tasks and the highest compression level for decompression tasks. Performing decompression is also always more energy efficient for both mobile platforms and the workstation platform. When comparing performance of three evaluation platforms, Pandaboard provides higher energy efficiency over Raspberry Pi and the workstation for the Local, Wired and Wireless experiments.

Several general observations are made across three systems:

- The lzop utility is the only utility which outperforms network transfer across all systems and all experiments for both throughput and energy efficiency.
- The utilities such as xz, pigz and gzip, while exceeding lzop on selected network experiments (the decompression in particular), often fail to outperform network throughput for compression or energy efficiency (either in another experiment or on another platform).
- For throughput and energy efficiency, it is always best to select the lowest compression level for compression and the highest compression level for decompression.
- The gain of using parallel utilities instead of sequential counterparts in networked experiments is limited by the compression ratio and the network upload and download throughputs, i.e., CR*T.UUP and CR*T.UDW.
- Scaling frequency down always reduces throughput.

- Scaling frequency down, when I_{idle} of 0 A, always produces higher energy efficiency.
- Scaling frequency down, when I_{idle} of 0.25 A or greater, always produces lower energy efficiency.

The findings can be used to direct energy optimizations of data transfers in mobile and workstation applications by encouraging development of data transfer frameworks that are conscientious of the mobile device's energy status. For example, a server could easily store multiple copies of the same file, compressed with different utilities and compression levels, to allow the mobile device to choose, based on its capabilities, currently available network bandwidth, energy status, and user preferences, which version of a file to download. Compression utility, such as lzop, can be integrated as a basic compression and decompression choice for software repositories, so that devices downloading files can automatically download the compressed file and decompress them on their systems. However, if proper condition such as slow network speed, is met, mobile device can instead download file compressed using the xz utility. Additionally, mobile devices, could decide which frequency level to use during download or upload of files.

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