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A \$35 Firewall for the Developing World

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ABSTRACT

A number of recent efforts aim to bridge the global digital divide, particularly with respect to Internet access. We take this endeavor one step further and argue that Internet access and web security go hand in glove in the developing world. To remedy the situation, we explore whether low-cost platforms, such as Raspberry Pi (\$35) and Cubieboard (\$59), can be used to implement security mechanisms. Using a firewall as a motivating security application we benchmark its performance on these platforms to test our thesis. Our results show that these platforms can indeed serve as enablers of security functions for small sized deployments in the developing world, while only consuming less than \$2.5 worth of electricity per device per annum. In addition, we argue that the use of these platforms also addresses maintenance challenges such as update roll-out and distribution. Furthermore, a number of additional network functions, such as caching and WAN acceleration can also be implemented atop this simple infrastructure. Finally, we posit that this deployment can be used for in-network monitoring to facilitate ICT4D research.

Categories and Subject Descriptors

C.2.0 [Computer-Communication Networks]: General—*Security and protection*; C.2.3 [Network Operations]: Network management

General Terms

Design, Human Factors, Performance

Keywords

Developing World, Middleboxes, Security, ICT4D

1. INTRODUCTION

Over the course of the last few decades, the Internet has matured into a repository of human knowledge, a medium for dissemination of ideas, and more generally, an all-encompassing portal for planet-scale connectivity. It has also become an integral part of the global economy. So much so that in the period between 2006 and 2011, it accounted for 21% of GDP growth in developed

countries [20]. In addition, maturity in the Internet ecosystem has resulted in a higher standard of life [20]. In the same vein, Internet access coupled with social media has become a catalyst for social, cultural, and political activism and change [32, 35, 33, 36]. While the Internet has been declared a basic human right [29], in reality more than two-thirds of the world population—which lives on less than two dollars a day [11]—does not have access to it. This Internet blackout can be attributed to a set of technological, social, and economic factors.

To bridge this connectivity gap, researchers, social entrepreneurs, and industry specialists have explored and deployed a number of radical solutions. These range from wireless networks driven by WiMAX [17, 10], satellite [21], ZigBee [27], long-distance WiFi [26], wireless mesh [16], and cellular links [14] to wired technologies enabled by optical, dial-up, and analog cable networks [23]. These backbone and last mile access network technologies are augmented by a similarly rich array of conventional and unconventional optimizations, including aggressive caching [5], prefetching and offline access [24], P2P content sharing [28], and village-level kiosks [8, 17]. Unfortunately, Internet backbone connectivity is still a bottleneck factor due to its high-cost [28]. This coupled with the limited data rate of some of these technologies, restricts end-user connectivity to the kilobit order. Cognizant of the potential of such a large untapped market, technology giants have also recently jumped into the fray, with Google and Facebook leading the way with Project Loon [12] and Internet.org [37], respectively.

Above all, the network security model in the developing world is considerably different than what the security research community and the technology industry has hitherto focused on [6, 7, 25]. This is evinced by the disproportionately high rate of cybercrime originating in developing countries. In addition, these countries reside on the higher end of the global spam scale as well as botnet activity [6]. On the one hand, these problems weaken the security and resilience of the worldwide Internet infrastructure and on the other, they hamper

widespread deployment by denting the confidence of the average user in technology. According to Ben-David *et al.*, the multi-faceted factors specific to developing countries include lack of regular online software and firmware updates due to limited bandwidth, shared computing resources, low-literacy of the users, and rampant software piracy [6].

1.1 Another Brick in the Firewall

Viruses are especially uncontrollable in Internet cafes—which are a primary source of connectivity for most users in the developing world—due to shared USB flash drives, untrained users, and limited financial and human resources [7]. Some researchers have gone to the extent of arguing that virus ecology and epidemiology in the developing world is fundamentally different than the developed world [25]. Furthermore, the networks in these regions are largely insecure due to the high cost of enterprise-grade middleboxes such as firewalls and thus the networks are susceptible to even simple port scans. Fortunately, the research community has started pushing for generalized middleboxes [30], although the target so far has been high-end applications [31].

In this paper, we explore how the recent calls for middlebox innovation can be leveraged to break the security status quo in the developing world. Specifically, we try to ascertain whether low-cost platforms such as the Raspberry Pi [13] and Cubieboard [3] can be used as middleboxes to implement firewall functionality to protect alternative network deployments or small Internet cafe level LANs. These networks include those supported by long-distance WiFi, WiMAX, and Zigbee, to name a few. While we benchmark the performance of a firewall application on these two platforms, our thesis is in no way limited to them. The case is equally applicable to other similar platforms such as Utilite [4], Arduino [1], and BeagleBoard [2]. In fact, as we discuss further on, platforms such as the NetFPGA are also viable options. Furthermore, the platforms can also be used to provide other security services such as local software upgrade patches and intrusion detection systems as well as more general middlebox applications such as content caching and traffic shaping.

The rest of the paper is organized as follows. In §2 we give an introduction to our target alternative networks and low-cost platforms. §3 presents our target application and its evaluation on two low-cost platforms. General use-cases and platforms are discussed in §4. We summarize relevant related work in §5 and finally conclude in §6.

2. BACKGROUND

In this section, we first present alternative networks which have been designed specifically for the developing world and then analyse various low-cost, single-chip

Technology	Net Bandwidth (Mbps)
ZigBee [27]	0.060
Satellite [21]	1
Wireless mesh [16]	2.5
Long-distance WiFi [26]	5
WiMAX [10]	6

Table 1: Comparison of Alternative Networks

devices.

2.1 Alternative Networks

Alternative networks augment existing technologies by customizing them to support low-cost, low-power, and low-maintenance. Table 1 lists the solutions that have been deployed in various locations around the world and their data rates. We discuss these in detail in this section.

Long-distance WiFi.

Long-distance WiFi initiatives extend the range of the specification by modifying the MAC layer. One such implementation, dubbed *WiLDNet* [26], addresses three shortcomings in the vanilla 802.11 protocol for long-distance communication: 1) sub-optimal link-level recovery, 2) frequent collisions due to CSMA/CA, and 3) inter-link interference. To this end, it uses bulk packet acknowledgement, TDMA enabled by loose time synchronization, and adaptive loss-recovery.

ZigBee.

Lo3, which stands for “Low-cost, Low-power, Local communication”, advocates the use of 802.15.4 for rural connectivity [27]. The use of 802.15.4 enables the setup to minimize its energy footprint by consuming power on the μ W and mW scale during idle and normal operation, respectively. To negate investment in a centralized tower, Lo3 makes use of a mesh network in which the medium is arbitrated by centralized TMEDA.

Satellite.

Satellite networks have also been employed for backbone connectivity in rural areas. For instance, in rural Zambia, VSAT (Very Small Aperture Terminal) satellite connections are being used to provide Internet connectivity [21]. This bandwidth is then distributed through a three-tier WLAN within the community: one main tower (wide-area backbone) connected to the VSATs and peered with other towers (local-area backbone), which in turn provide connectivity to end-hosts through Ethernet and wireless access points.

WiMAX.

WiMAX greatly reduces the cost of network deployment and also increases its reach to rural areas where

Component	Raspberry Pi (Model B)	Cubieboard
Processor (MHz)	700	1000
GPU (GLFOPS)	24	7.2
Memory (MB)	512	1024
Ethernet	10/100	10/100
Price (\$)	35	59

Table 2: Feature-based Comparison of Platforms

the geographic terrain is not amenable to copper and optical wiring. Lele *et al.* [17] advocate the use of such a deployment in rural India, where a single WiMAX base station serves the entire community. Architecturally, it revolves around a kiosk model in which end-users with regular telephone sets are connected to kiosks which in turn communicate with the base station.

Wireless Mesh.

As opposed to mainstream urban networks—which depend on well planned antenna configurations and nodes with multiple radios—networks designed for rural areas in the developing world rely on nodes with single radios [16]. This ensures low cost and simplicity which are first-class goals for these networks. The single radio nodes are connected in the form of a mesh to provide connectivity at the community level. End-hosts therefore are connected through multiple hops to the gateway.

2.2 Basic Platforms

In this section, we first give a feature-set overview of the Raspberry Pi [13] followed by Cubieboard [3].

Raspberry Pi.

Raspberry Pi is powered by a Broadcom system-on-chip multimedia processor with an ARM 1176JZF-S 700MHz processor and a VideoCore IV 24GFLOPS GPU. For storage it relies on an external MMC or SD Card. Available in two models (A: 256MB RAM, 1 USB port, and B: 512MB RAM, 2 USB ports, and 10/100 Ethernet), it can be interfaced with external components via GPIO (General-purpose Input/Output) and UART (Universal Asynchronous Receiver/Transmitter). On the software side, a number of popular Linux distributions, such as Debian and Fedora have Raspberry Pi specific versions.

Cubieboard.

Cubieboard consists of an AllWinner A10 system-on-chip processor with an ARM Cortex-A8 1GHz processor and a Mali 400 7.2GFLOPS GPU. For storage, it relies on both built-in 4GB NAND Flash and external slots for microSD and SATA. Moreover, it has 1GB RAM and 10/100 Ethernet. External interfacing is enabled

by 2X USB slots, I^2C (Inter-Integrated Circuit), SPI (Serial Peripheral Interface), and LVDS (Low-voltage Differential Signaling). Similar to the Raspberry Pi, the Cubieboard is also driven by Debian and Fedora based distributions.

Table 2 compares the key features of both platforms.

3. MOTIVATING APPLICATION

Developing world countries—such as India, China, and Brazil—are top sources of spam and botnet activity. To make matters worse, the number of botnets in these countries is expected to exceed the developed world soon due to the increase in digital connectivity as well as the poor security hygiene of the area [34]. Therefore, in the future, Internet security battle-lines will be drawn in the developing world.

Traditionally, firewalls have been employed to stem the botnet tide. Firewalls provide a first line of defense on the network against malicious activity. Each firewall has a list of rules that it enforces to keep unwanted traffic at bay. These rules decide if a certain flow is to be accepted or rejected. In addition, these rules can work at multiple levels in the protocol stack from the link layer up to the application layer. Naturally, the efficacy of any firewall is determined by its ruleset. Multiple rules in tandem can be used (in the form of a rule chain) to implement complex filtering policies. A key requirement is the ability to filter packets at line-rate otherwise the network experiences a decrease in QoS. Therefore, enterprise-grade firewalls are designed to achieve fast processing while providing rich features such as policy-based filtering and deep packet inspection. Unfortunately, enterprise-grade firewalls (and middleboxes in general) are cost-prohibitive. At the other end of the spectrum, general-purpose machines can be employed to perform basic firewalling.

The aim of this paper is to explore the use of the most basic platforms for firewall functionality. To this end, we use real-world firewall rule set cardinality to gauge the throughput of low-cost platforms to protect alternative networks in the developing world. These platforms can be considered as an example of commodity off-the-shelf hardware which is more appropriate for these regions [26]. Architecturally, we envision these firewalls to be present at the backbone of alternative networks such as those supported by long-distance WiFi or at the network gateway of Internet cafes. According to figures from 2009, the average firewall contains 800 rules and the maximum number in the wild is 20000 [9]. Therefore, we use these numbers for our benchmarking.

3.1 Setup and Results

In this section, we present the results from our evaluation of Raspberry Pi and Cubieboard. We used the standard `iptables` application in Linux as our test fire-

Chain	Function
PREROUTING	Pre-routing decision packets
POSTROUTING	Post-routing decision packets
INPUT	Incoming packets for local delivery
OUTPUT	Outgoing packets
FORWARD	Incoming packets for non-local delivery

Table 3: Default iptables chains

wall. `iptables` allows the user-space configuration of *chains* of rules (default chains enumerated in Table 3) of the kernel firewall (`Netfilter`) for IPv4. Stateful rules that `ACCEPT`, `REJECT`, `DROP`¹, or `LOG` a packet can be added to these chains.

By default, the `iptables` module is not available in the stock kernel disk image of both platforms. Therefore, we linked the module in and recompiled the kernel for a Linux distribution for each platform. For Raspberry Pi we used a Wheezy Raspbian image with kernel version 3.6.11 while for Cubieboard we used a disk image from Linaro with kernel version 3.10.1. As our goal was to measure the performance in terms of flow forwarding of each platform subject to firewall filtering, we used `iperf`² to measure throughput between the platform and a standard host (a single hop away). We used the default settings for `iperf` which use TCP as the transport with a window size of 16KB. A custom script was used to add random rules to `iptables`. Figure 1 plots the throughput of each platform as a function of the number of firewall rules. Without any rules, Raspberry Pi has a throughput of around 58Mbps as opposed to 54Mbps for Cubieboard. As we increase the number of rules, the performance of Cubieboard degrades more gracefully in comparison to Raspberry Pi. This is due to the higher processing power of Cubieboard (1GHz) versus Raspberry Pi (700MHz). While relative numbers are immaterial for our cause, the analysis shows that both platforms are capable of sufficient throughput (20Mbps Raspberry Pi and 30Mbps Cubieboard) for an average number of firewall rules (800) in the wild [9].

4. DISCUSSION

The use of low-cost platforms simplifies update rollout and also enables additional functions such as content caching and remote monitoring while ensuring a low energy footprint. We discuss these and other topics in this section.

4.1 Update Rollout

As mentioned earlier, one of the challenges in providing security (or any technology) in the developing world

¹As opposed to `REJECT` in which the source is notified, `DROP` silently drops the packet without any source notification.

²`iperf` allows the measurement of throughput for TCP and UDP streams between two end-hosts.

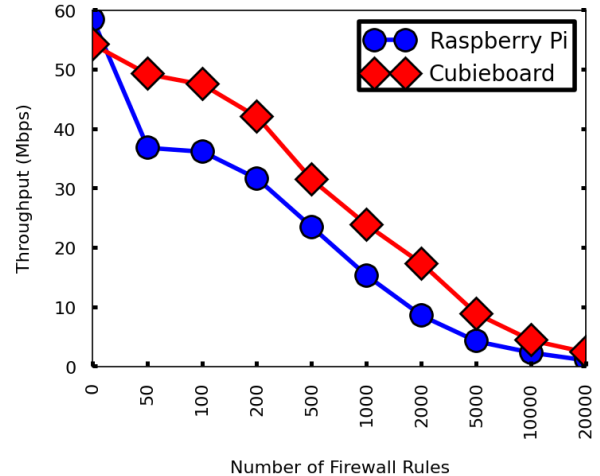


Figure 1: Raspberry Pi vs. Cubieboard

is the low-literacy of both service providers as well as end-users. In addition, the high cost of maintenance is a major impediment. Therefore, it is useful to have systems that can be easily be upgraded and maintained. To this end, SD Card support on low-cost platforms simplifies application and ruleset rollout. For instance, the OS pre-loaded with firewall rules can be supplied as an SD Card image and quickly disseminated through self-replication [22]. In addition, extra rules can be downloaded from the Internet on the fly as rules specific to the local network evolve.

4.2 Higher Performance

For alternative networks, the 30Mbps for an average number of firewall rules suffices. For networks with higher bandwidth requirements, NetFPGA-like platforms can be employed. NetFPGA-1G consists of 4 x 1Gb interfaces while the recent 10G version features 4 x 10Gb ports. The customized hardware (PCI board with FPGA) and firewall software can enable near line-rate processing.

4.3 Additional Functions

The extra CPU cycles and storage on the platform can be employed for additional applications. For instance, the storage can be used to provide network wide caching [5]. This will assist in keeping bandwidth usage in check. Moreover, due to the volatility of these networks, connectivity is intermittent. In such situations, popular content can be served from the firewall platform for temporary offline access. Other potential applications include WAN acceleration and pre-fetching [24].

4.4 Distributed Firewalls

Rule management can be further simplified by enabling distributed firewalls [15]. In this architecture,

we envision a centralized service which maintains lists of firewall policies. These lists can be distributed based on geography or network behaviour similarity. These rules can then be rolled out to Raspberry Pi or Cubieboard-enabled platforms via IPSec mechanisms, for enforcement at the edge.

4.5 NAT

An additional function that firewalls afford is network address translation. NATs assist in obfuscating internal addresses. Internet cafes which are still thriving in the developing world can benefit from this in two key ways: 1) they can protect internal machines from malicious traffic and 2) they can enable simple subnet allocations for devices behind the NAT.

4.6 Monitoring

We envision that each local device will also be connected to a central server³ and will periodically communicate different network statistics. This monitoring will help in understanding the dynamics of firewalls in the developing world and in devising new firewall rules. In addition, these statistics will also enable ICT4D practitioners and researchers to understand the usage patterns of devices and users in the wild. Finally, remote monitoring will aid in diagnosing network-level problems which are beyond the skill-set of the local workforce [8].

4.7 Energy Footprint

As power is a constrained resource in the developing world [8], it is imperative to minimize the energy footprint of any additional infrastructure. Fortunately, Raspberry Pi-like platforms draw minimal power. Raspberry Pi Model B has a power rating of 3.5W, therefore it will draw a maximum of 84W in a day. With an average cost of 8cents/kWh in India [18], a quick back-of-the-envelope calculation reveals that the energy cost of an always-on Raspberry Pi Model B powered firewall is \$0.01 daily or \$2.45 annually, which makes it affordable for widespread deployment. In fact, it can even be removed from the power grid and powered by batteries to avoid equipment failure due to high power fluctuation in these regions [8].

5. RELATED WORK

Our work is inspired by Ben-David *et al.* [6] who argue that security issues in the developing world are fundamentally different than the developed world. In particular, our firewall analysis is motivated by their insight that this not only has an adverse effect on the

³We do not necessarily mean a single server per se but potentially a geo-distributed architecture that maintains either local or global network state.

global technological landscape but also hinders technology adoption in the developing world. In a similar vein, [25] has also argued for security solutions designed specifically for the developing world. To this end, Innoculous is a self-contained tamper-proof anti-virus system on a flash drive for virus detection and profiling [25]. Similarly, Bhattacharya and Thies [7] present the dynamics of viruses in Internet cafes in India. They also highlight a number of research opportunities including computer virus epidemiology, use of disk imaging for simple roll-back, taking advantage of loose privacy norms, and leveraging the want of the owners to pay more for virus reduction, such as subscription based training and updated virus definitions via post. Our approach of provisioning firewall rules along with the OS stack as a disk image is a direct consequence of their recommendations. While all of these proposals target security in the developing world, to the best of our knowledge this paper is the first attempt at employing low-cost platforms for network security applications. Finally, our work has benefited from the rich body of work [17, 10, 21, 27, 26, 16, 14, 23, 5, 24, 28, 8, 17] that aims at providing low-cost connectivity in the developing world.

6. CONCLUSION

We explored the use of low-cost platforms such as Raspberry Pi and Cubieboard for security applications in the developing world. Our benchmarking of a firewall proves that the capabilities of these platforms are sufficient to fill the security void in developing regions. Using an average number of firewall rules, we showed that a Cubieboard can achieve throughput of 30Mbps. The use of low-cost platforms also simplifies application rollout in the form of an SD Card image. In addition, the power draw of the deployment is small enough to make it feasible and sustainable. We also discussed how the same platform can be used for general networking applications such as WAN acceleration and content caching and pre-fetching. Moreover, remote monitoring of these platforms can both aid in network diagnostics as well as enhancing ICT4D research by laying bare the characteristics of network traffic and user behaviour in the developing world.

In addition to field-testing and real-world deployment, we are also interested in writing custom security applications such as firewalls and wrapping each in a Mirage unikernel [19] and running it directly on baremetal Raspberry Pi-like platforms. This has two main advantages: 1) It simplifies application shipment by turning the entire stack into a single image and 2) It enhances the security of the application itself by making its code type safe and sealing it against runtime modification.

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