C. Comparison of VPN Solutions

This section compares and evaluates the performance results as well as important non-functional aspects that distinguish the studied VPN solutions.

1) Performance: Fig. 3 summarizes the individual performance rankings for each platform. Since the platforms contained Ethernet devices of different speeds, the measurements were normalized to the same order of magnitude, in order to make their relative distance from the baseline (the theoretically possible) comparable. The evaluation showed a clear trend towards the latest approaches MACsec and Wireguard. While MACsec (together with IPsec) was consistently best or second best performing solution for latency, Wireguard showed the highest throughput achievable (or line speed) on 4 of 5 platforms.

For 10 Gbit/s links, the equations seem to change considerably. In order to saturate these links, hardware support for encryption and big CPUs are not sufficient anymore and the bottleneck moved somewhere else. Where to, we can only speculate.

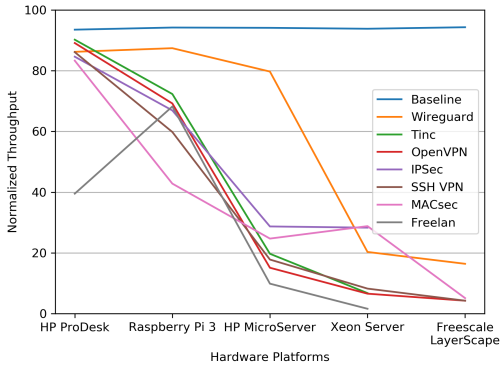
2) Non-functional Aspects: The customary and established solutions (OpenVPN, IPsec, Tinc, Secure Shell) offer a multitude of ciphers to choose from. And, while variety is ostensibly a good feature, it has detrimental effects as well.

Some solutions offer ciphers in their documentation, but once configured just do not work (see Table III) and furthermore, the sets of working algorithms change between platforms. We could not find conclusive evidence as to why this is the case. It is at least puzzling, as all platforms ran an up-to-date Linux kernel, with, in most cases, a current software distribution on top (see Table II). Some ciphers even worked on none of the tested platforms. Within the ciphers that did work, some individual ciphers (e. g. Whirlpool, MCDC-2) always showed abysmal performance. The modes of operation CFB1 and CFB8 also performed very badly, independently of the configured cipher. Other ciphers showed very good and very poor performance depending on the platform (e. g. BLAKE2). Furthermore, some ciphers are so old, that they have been broken by now, and must be considered insecure. Blowfish was proposed in 1993 and is even still the default setting for OpenVPN. Legacy support cannot be used as an argument here. Performance of the ciphers between platforms also differs widely. If performance actually is an issue, tweaking of the individual system becomes necessary and as we have showed, this is a non-trivial task.

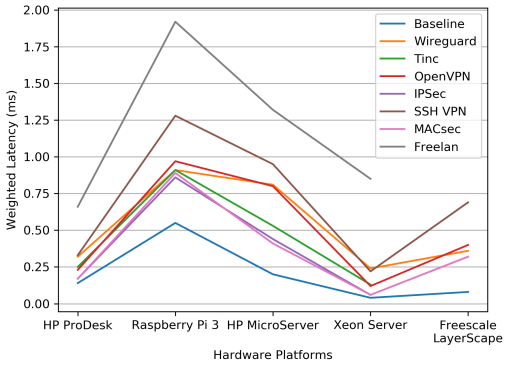
This wealth of options, that probably accumulated over many years of development and maintenance of each VPN software, seems to make it hard to manage it. In our minds, users would be better served, if the configurable cipher sets would be drastically reduced.

On contrast, the new approaches MACsec and especially Wireguard go in the opposite direction and do not offer the user multiple ciphers, thereby eliminating the chance for misconfiguration. Additionally, this gives the software developers the chance to address performance and compatibility issues, that may arise on different hardware and operating system architectures. Therefore, we clearly recommend the use of those two solutions, wherever possible.

[9]Normalization factors for the platforms were 0.1, 1, 0.1, 0.01, 0.1



(a) Throughput ranking.[9]



(b) Latency ranking.

Figure 3: General performance rankings of solutions over all platforms.

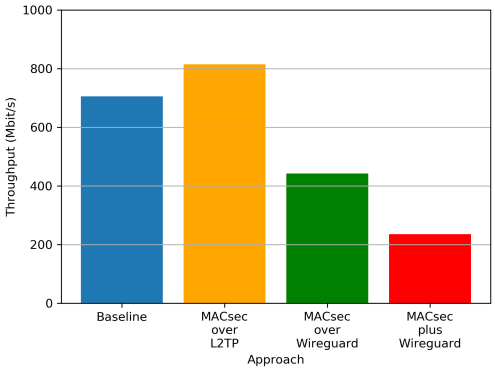
D. Extended Setting

Fig. 4 shows the achieved throughput and latency performances of each approach.

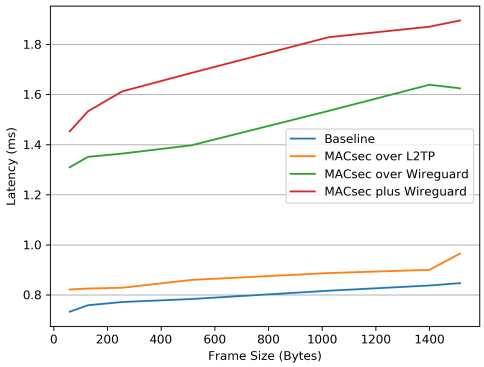
The throughput of the baseline measurement is lower than the measurement for MACsec/L2TP. This is probably due to the measurement tools rate adjustment algorithm getting confused by the setup, meaning the data flows being interrupted by multiple send and receive queues of the different involved devices. The measured CPU usage does not indicate a bottleneck.

The performance of the 'MACsec over L2TP'-approach shows almost line speed. This is no surprise, as the gateways only relay already encrypted frames. Yet, with the other two approaches, the performance drops considerably. The additional encryption steps performed on the gateways, have big impact. The additional Wireguard tunnel within the second approach halves achieved throughput and almost doubles latency. The further step of the third approach of de- and encrypting the MACsec frames on the gateways halves the achievable throughput yet again.

For resource restricted environments, where performance is non the less an issue, it seems unfeasible to protect communication data within and in between LANs with conventional means (second and third approach). Therefore, the aforementioned trade-off between configuration complexity and performance should be answered individually depending on



(a) Throughput comparison.



(b) Latency comparison.

Figure 4: Performance comparison of different approaches of the extended gateway setting.

the use case. The first prototypical approach of just relaying MACsec frames should be investigated further.

VI. Conclusion

This study investigated different software solutions on how to securely interconnect local area networks. Non-functional aspects as well as their performance were analyzed, discussed and compared.

The classic and well established solutions, like OpenVPN and IPsec, were found to exhibit significant drawbacks in the face of new and upcoming solutions. We believe, that these, namely MACsec and Wireguard, should be preferred in the future, where and whenever possible.

This study also revealed starting points for future research. ChaCha/Poly1305 performed best in resource restricted environments, where AES hardware acceleration within the CPU did not exist. It might therefore be promising to include this cipher into other VPN solutions and protocols in order to increase their performance in certain use cases. Furthermore, extended security schemes, that already protect communication data within a LAN should be further researched in order to be used efficiently.

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