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Towards securing the Internet of Things with QUIC

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2020-2-23

QUIC on IoT devices

Why? Reuse & leverage

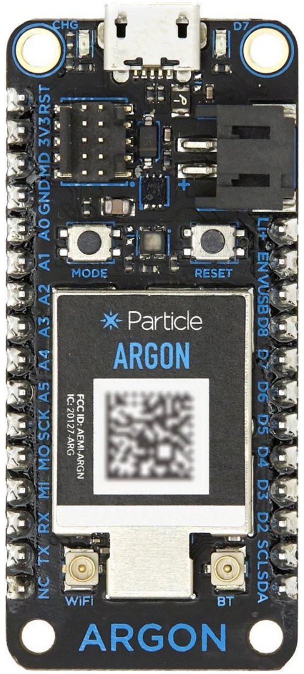
Warpcore

- **Minimal, BSD-licensed, zero-copy UDP/IP/Eth stack**
- Meant to run on netmap,
  can use Socket API as fallback
- 3700 LoC (+ 3000 LoC w/netmap), C
- Exports generic zero-copy API
- **Device OS has LWIP** =
  just works (after some patch submissions)
- **RIOT has GNRC** = needs own backend
  - RIOT port of LWIP unfortunately broken
  - GNRC lacks key features (poll/select, IPv4, etc.)

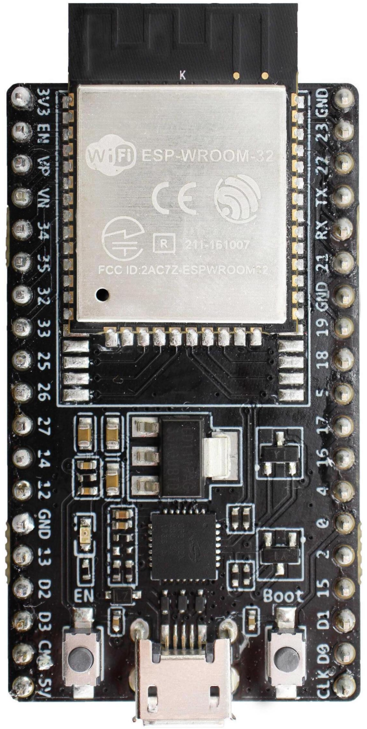
Quant

- **QUIC *transport* stack** (i.e., no H3)
  - Focus: high-perf datacenter networking
  - Client and server modes
  - 10,300 LoC, C
- **Warpcore for UDP**, otherwise uses:
  - **khash** (from klib, modified)
  - **timing wheels** (Ahern’s timeout.c, modified)
  - **tree.h** (from FreeBSD, modified)
  - **bitset.h** (from FreeBSD, modified)
  - **picotls** (Kazuho Oku)
    - **cifra**
    - **micro-ecc**

System hardware and software



Particle Argon	Platform	ESP32-DevKitC V4
Nordic Semiconductor nRF52840	**SoC**	ESP32-D0WDQ6
ARM Cortex-M4F	**CPU**	Tensilica Xtensa LX6
32-bit	**Instruction set**	32-bit
64 MHz	**Clock speed**	240 MHz
IEEE 754 single-precision	**FPU**	IEEE 754 single-precision
ARM TrustZone CryptoCell-310	**HW crypto**	AES, SHA, RSA, and ECC
256 KB	**RAM**	520 KB
1 MB (+ 4 MB SPI)	**Flash**	4 MB
4 KB EEPROM (emulated)	**Other mem.**	96 B e-Fuse
IEEE 802.11 b/g/n	**WLAN**	IEEE 802.11 b/g/n
Device OS 1.4.3	**OS**	RIOT-OS 2019.10
arm-none-eabi-gcc 5.3.1	**Toolchain**	xtensa-esp32-elf-gcc 5.2.0

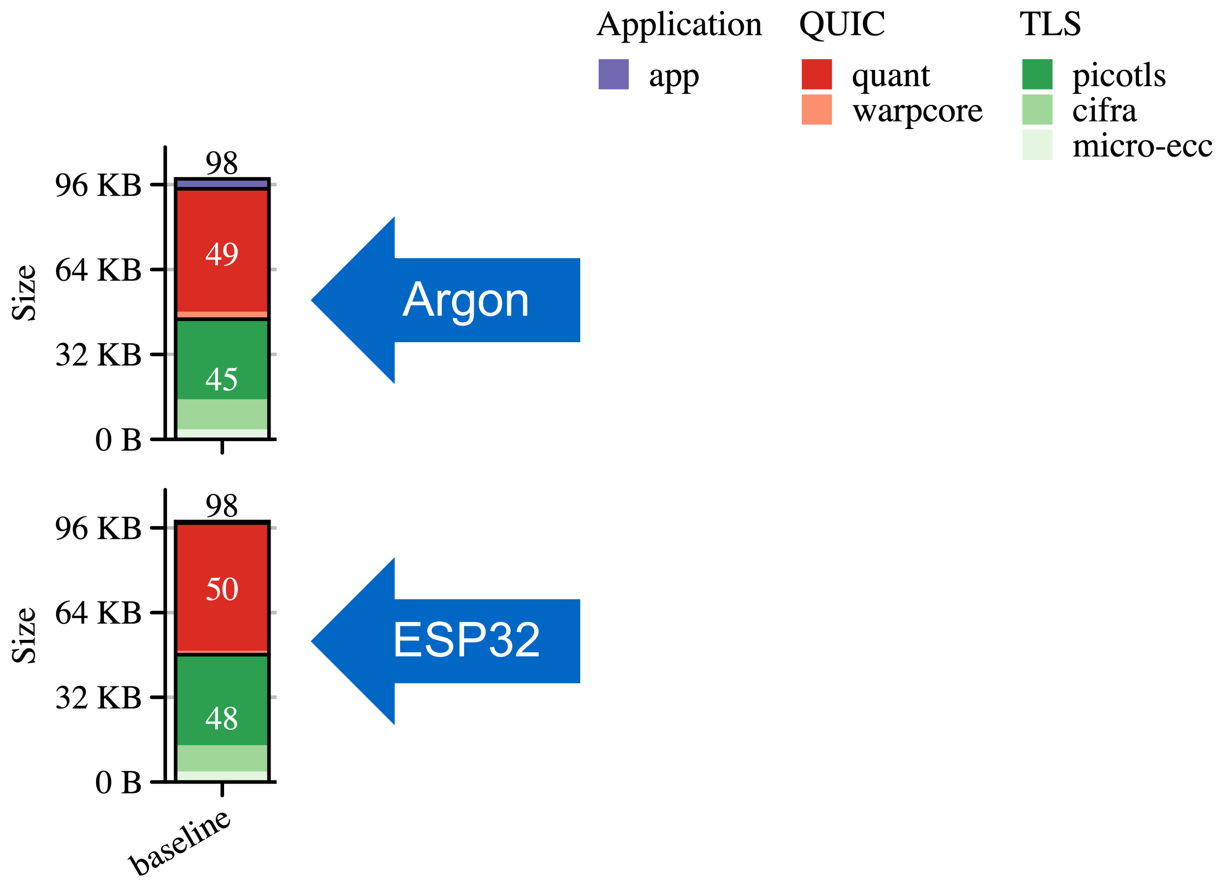


Measurements

Code and static data size

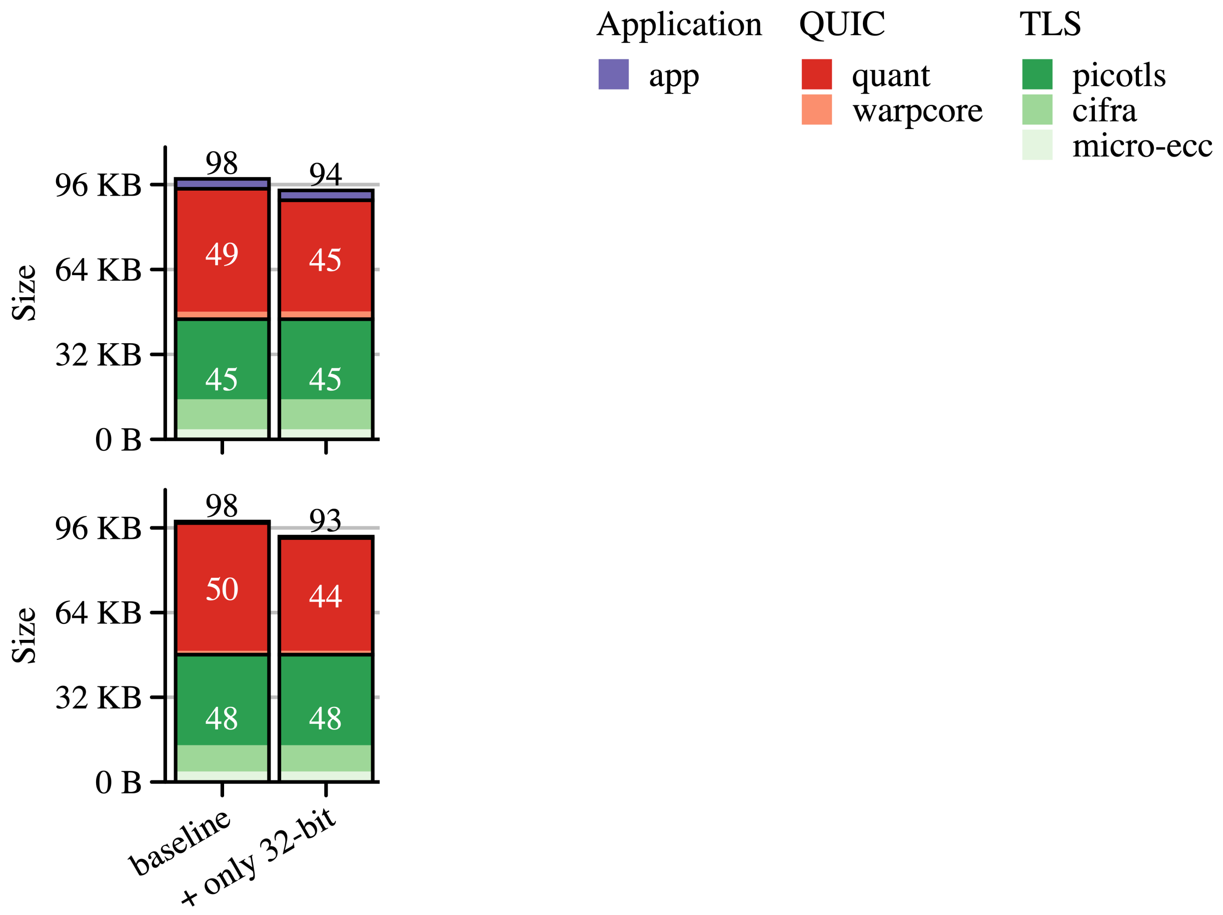
Build size: baseline

- Compiled code and static data size
- **Application**
  - Argon app has more features, hence larger
- **QUIC**
  - Already only uses single-precision FP
- **TLS**



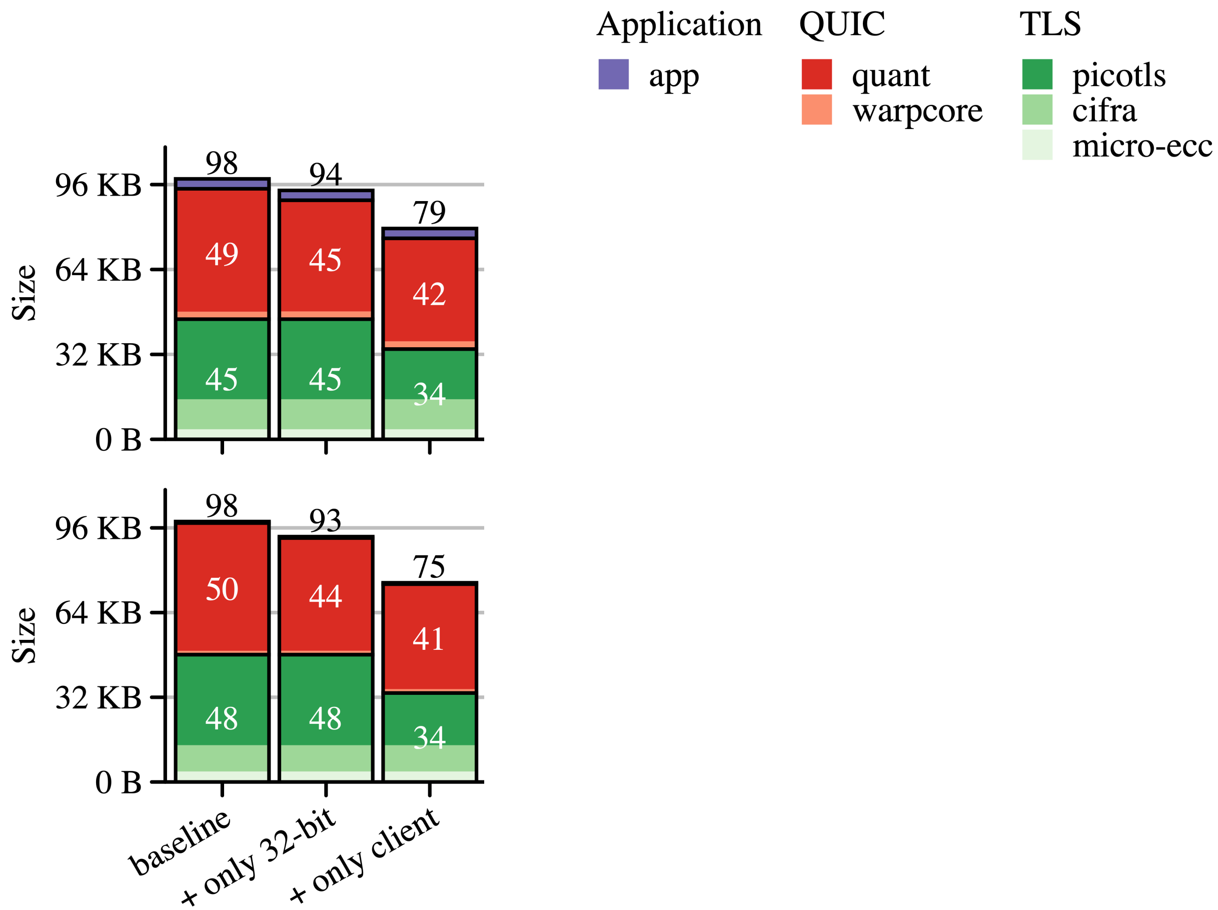
Build size: 32-bit optimizations

- **Eliminate costliest 64-bit math**, i.e., division and modulus
  - All are by constants, can multiply by magic number and right shift
- **Use 32-bit width** for many internal variables, e.g.,
  - Packet numbers
  - Window sizes
  - RTT (μs)
- **Not *fully* spec-conformant**, but unlikely to matter in practice for IoT



Build sizes: client-only mode

- **Disable server functionality**
- Unlikely to be of much use for IoT, esp. when battery-powered
- Also makes client use zero-length CIDs
- Large gain at the TLS layer!



- (Server-only mode: future work)

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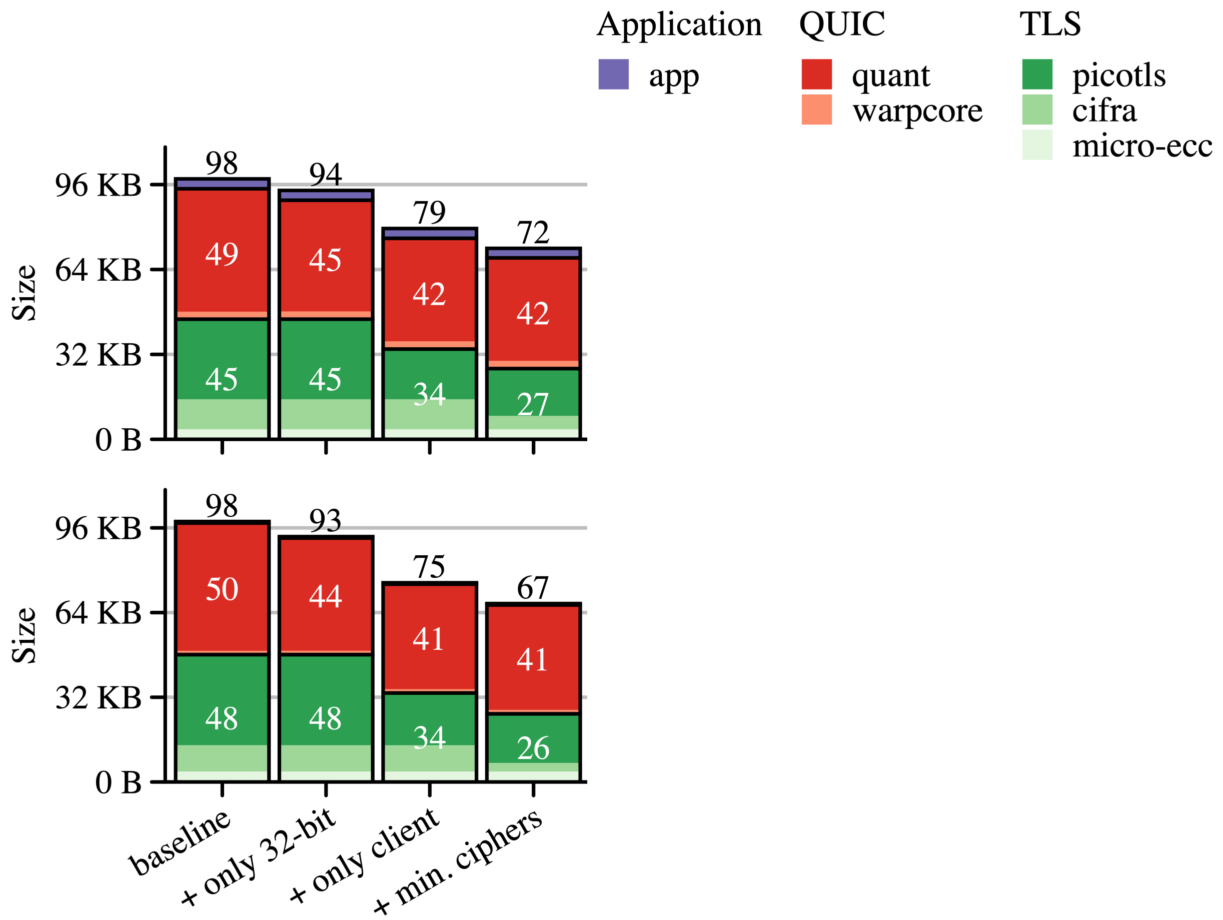
Build sizes: minimally-required crypto

- **Disable non-required crypto**, leaving
  - TLS_AES_128_GCM_SHA256 cipher suite
  - secp256r1 key exchange
- More gains at the TLS layer!
- **Could fully eliminate cifra & micro-ecc** *if* HW crypto was accessible from OSs...
- Together, reductions of 25-30% so far, without much loss in functionality
- Can save more by turning off functionality...



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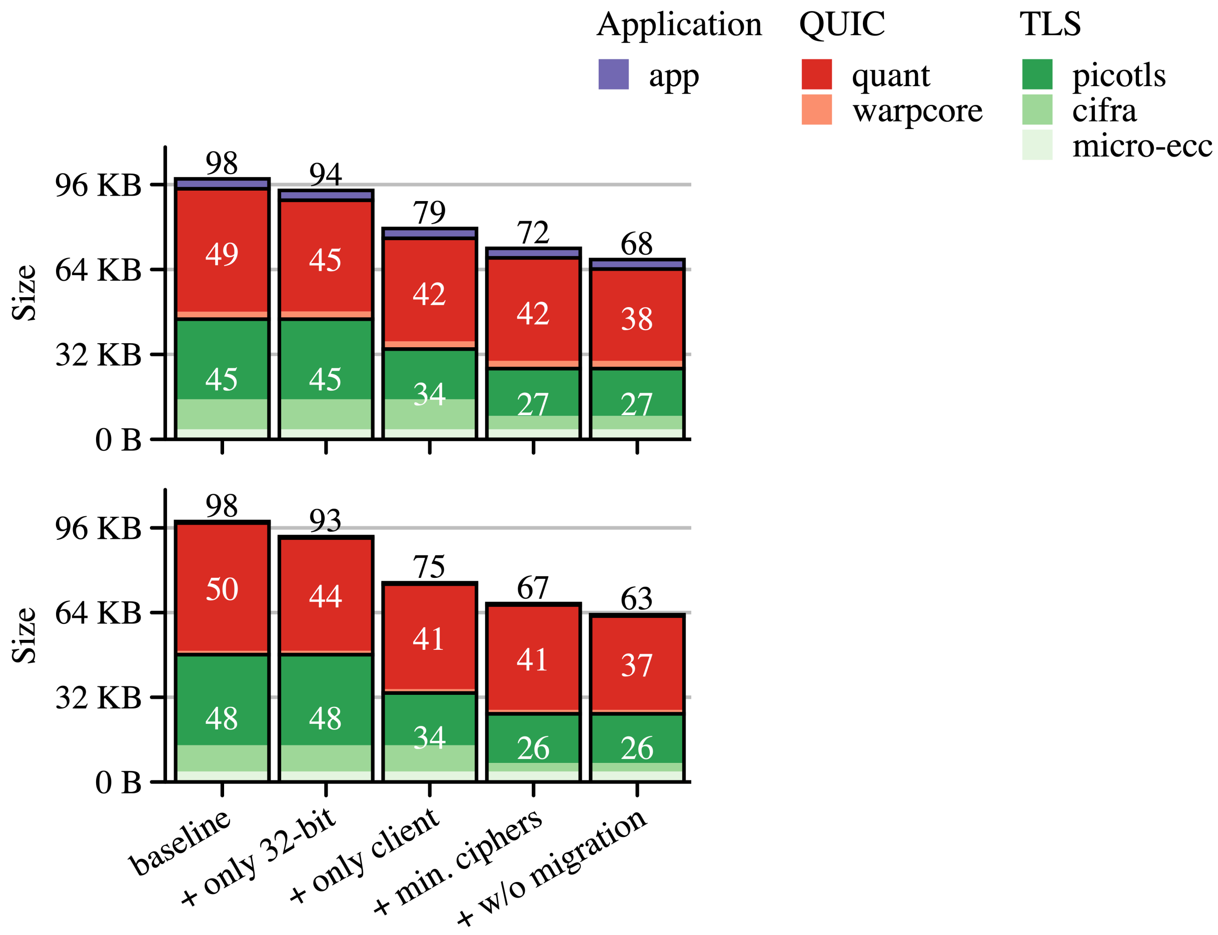
Build sizes: no migration

- **Connection migration** = switching an established connection to a new path
- Likely **unnecessary for IoT** usage



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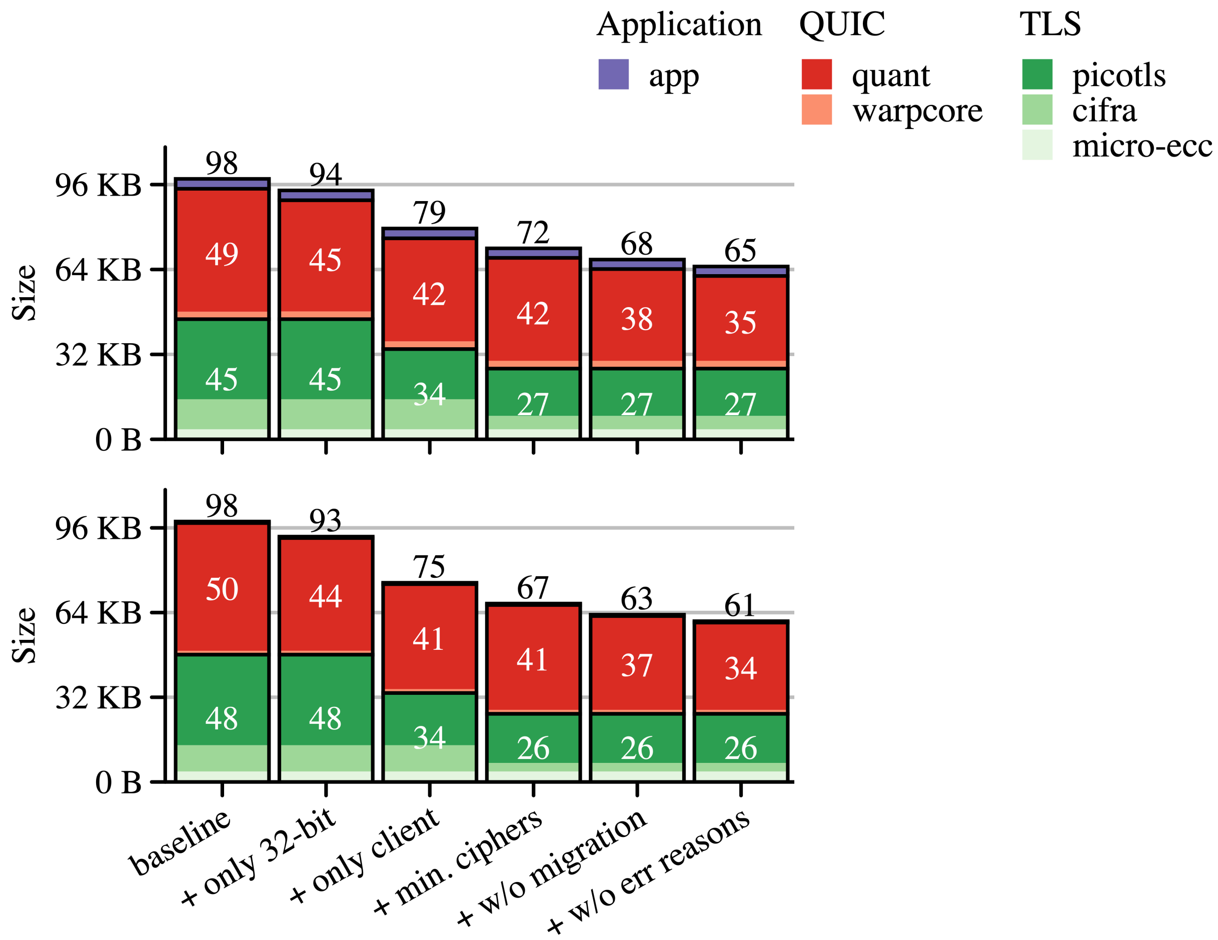
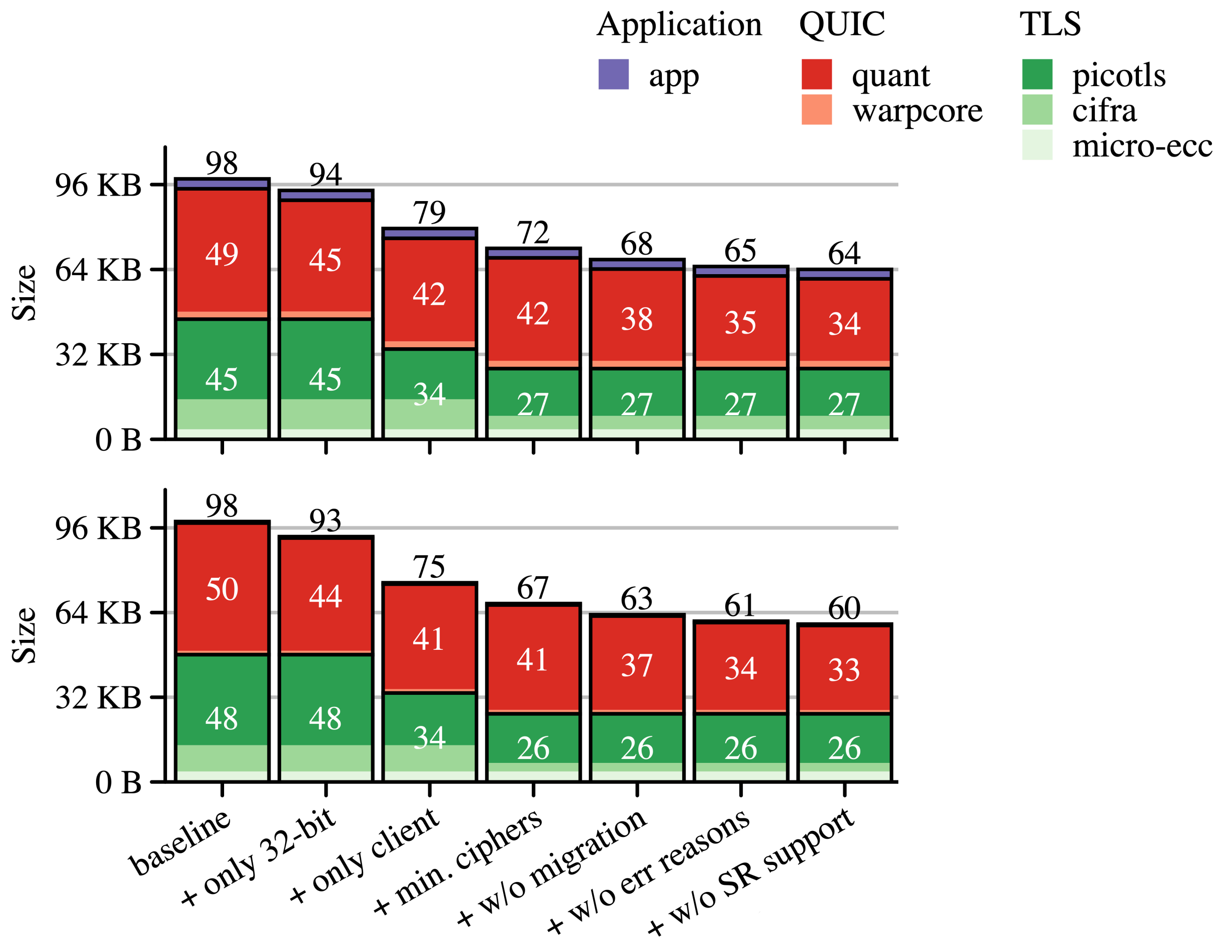
Build sizes: no error reasons

- QUIC allows **plaintext “reason” strings** in CONNECTION_CLOSE frames
- No protocol usage, only for human consumption
- Quant by default uses those heavily & verbosely
- So don’t



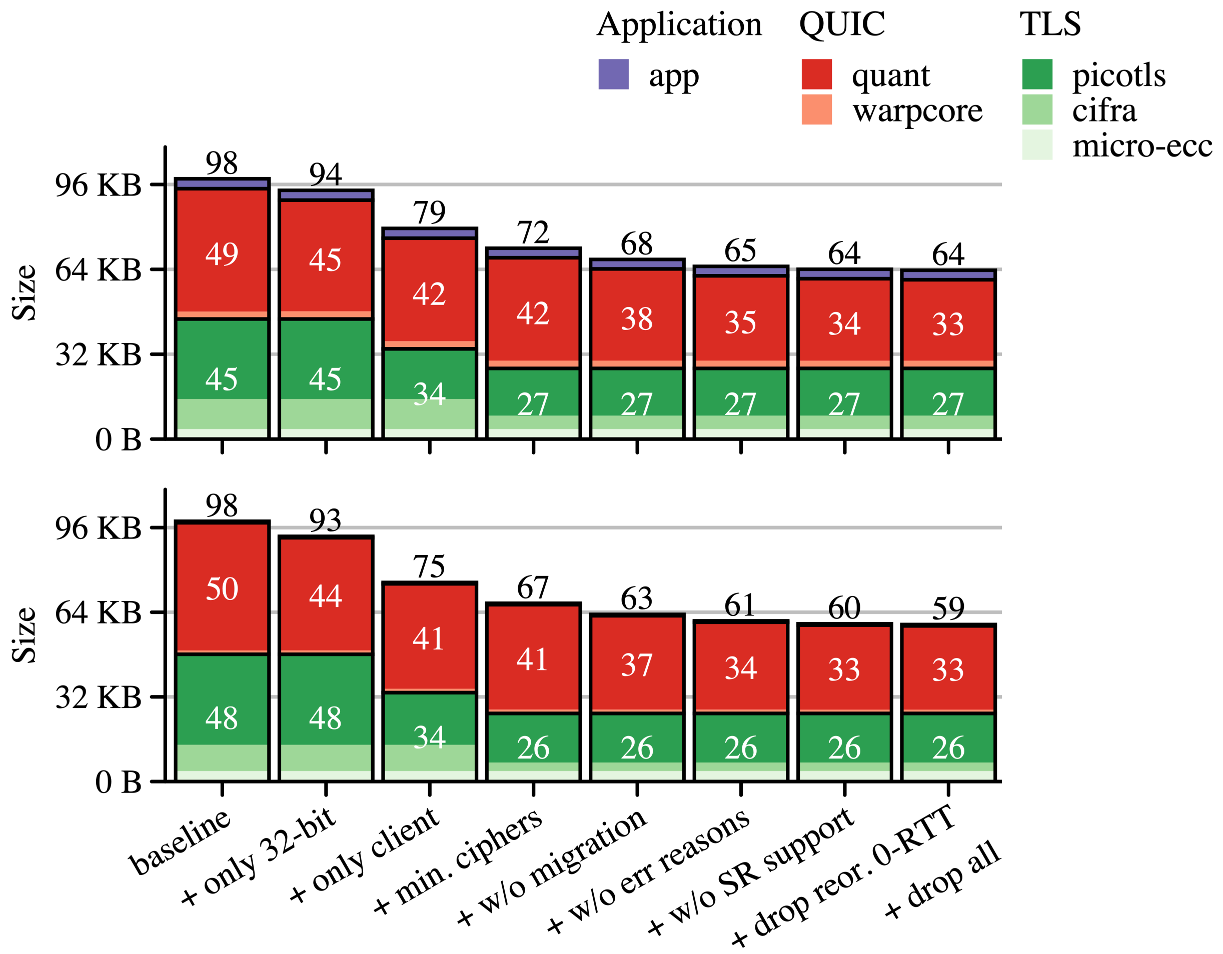
Build sizes: no stateless resets

- **Stateless reset** = signal to peer that local end has no more state for a connection
- To handle, need to be able to identify *which* connection RX'ed SR is for
- **Tradeoff:** handle SR vs. needlessly RTX



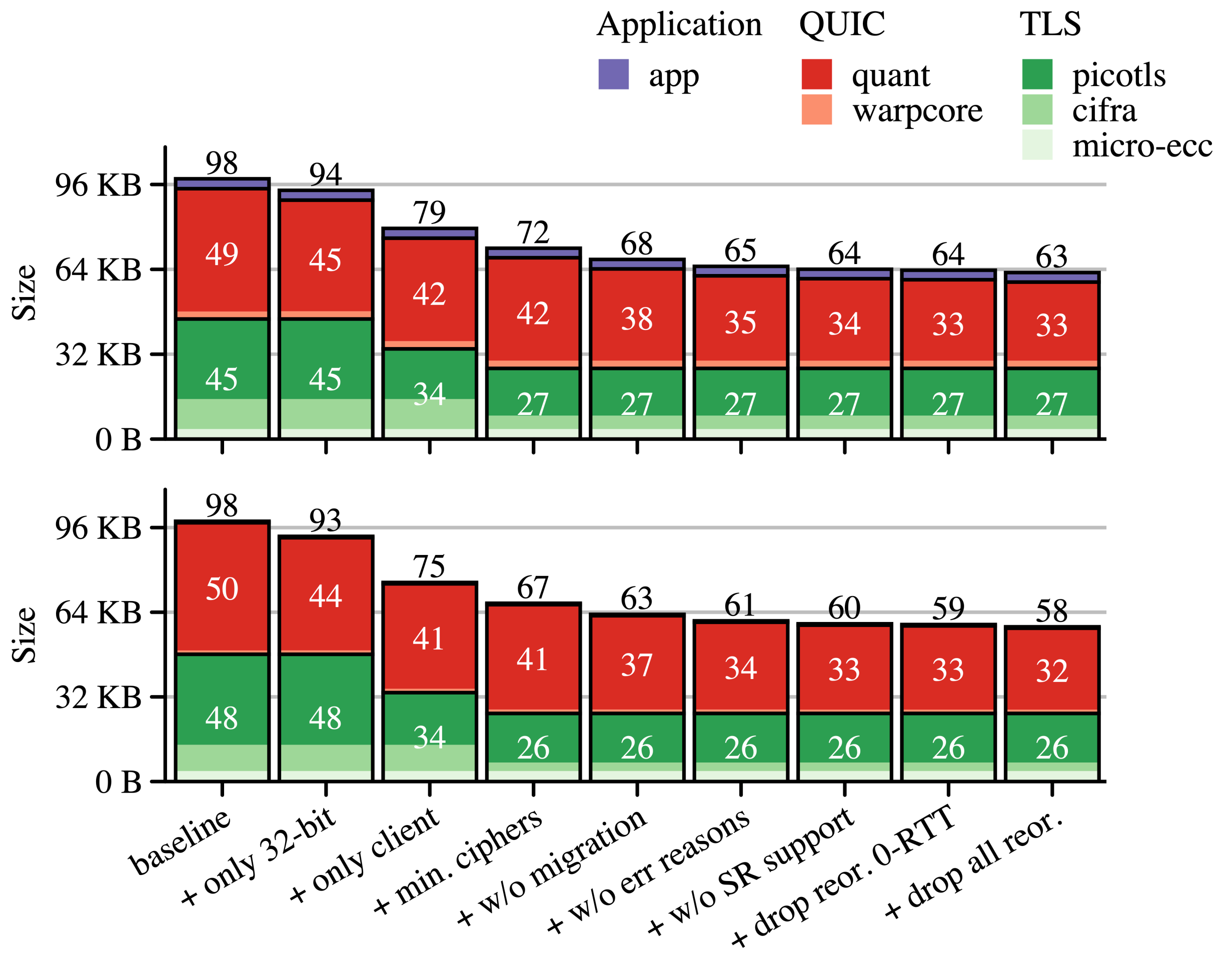
Build sizes: drop reordered 0-RTT

- Caching 0-RTT packets arriving out-of-order can avoid RTX
- Also has an overhead
- **Tradeoff:** cache vs. force RTX



Build sizes: drop *all* reordered data

- Caching *any* out-of-order CRYPTO or STREAM data can avoid RTX
- Also has an overhead
- **Tradeoff:** cache vs. force RTX

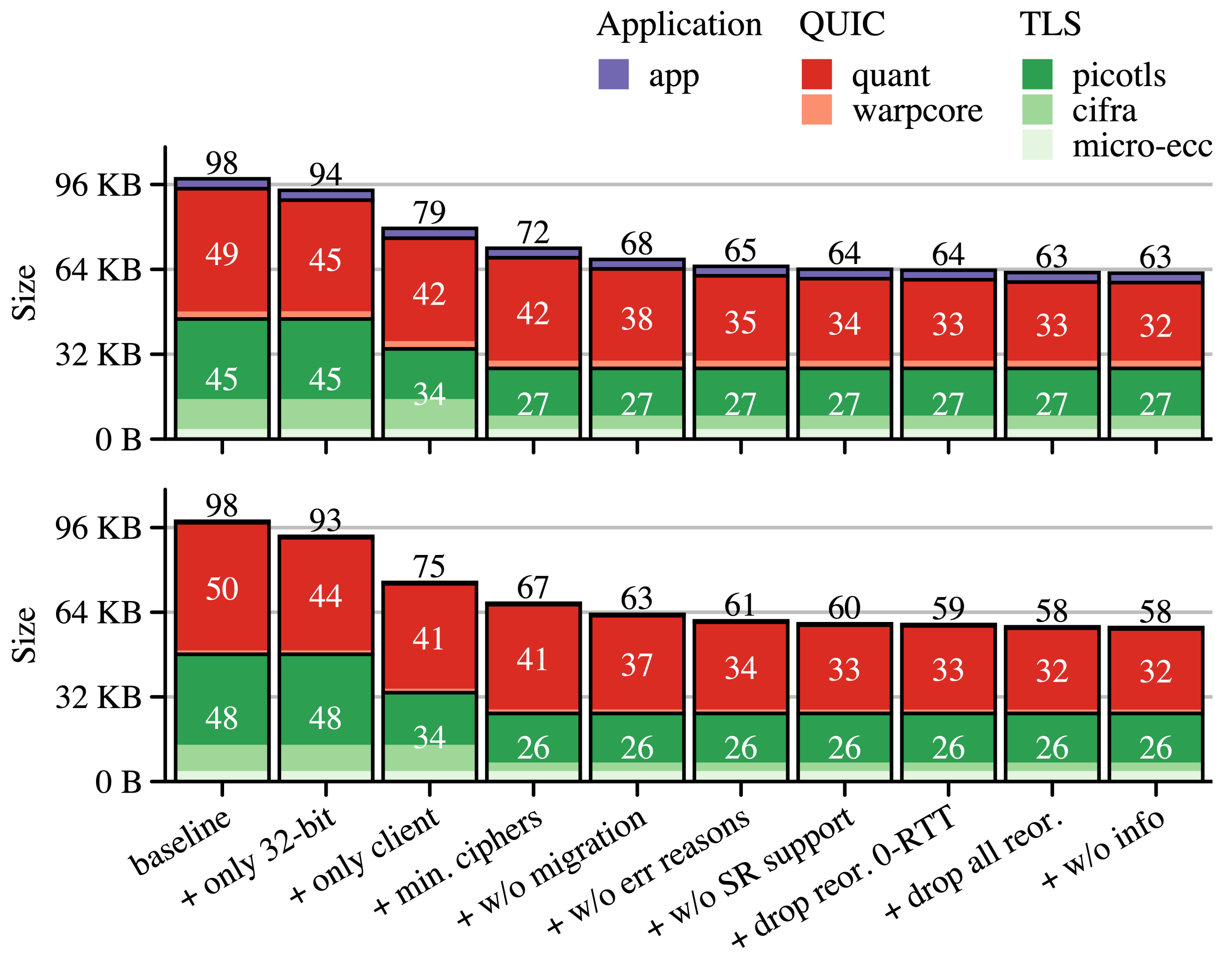


Build sizes: don’t maintain connection info

- Quant maintains a TCP_INFO-like struct about each connection:

```
pkts_in_valid = 40
pkts_in_invalid = 0
pkts_out = 10
pkts_out_lost = 0
pkts_out_rtx = 0
rtt = 0.049 (min = 0.000, max = 0.087, var = 0.027)
cwnd = 14840 (max = 14840)
ssthresh = 0
pto_cnt = 0
frame                   code        out         in
PADDING                 0x00       2941       1214
PING                    0x01          1          1
ACK                     0x02          6          7
CRYPTO                  0x06          3          5
NEW_TOKEN               0x07          0          3
STREAM                  0x08          1         29
MAX_STREAM_DATA         0x11          1          0
NEW_CONNECTION_ID       0x18          3          1
RETIRE_CONNECTION_ID    0x19          1          2
CONNECTION_CLOSE_APP    0x1d          1          1
HANDSHAKE_DONE          0x1e          0          2
strm_frms_in_seq = 33
strm_frms_in_ooo = 1
strm_frms_in_dup = 0
strm_frms_in_ign = 0
```

- Don’t do that

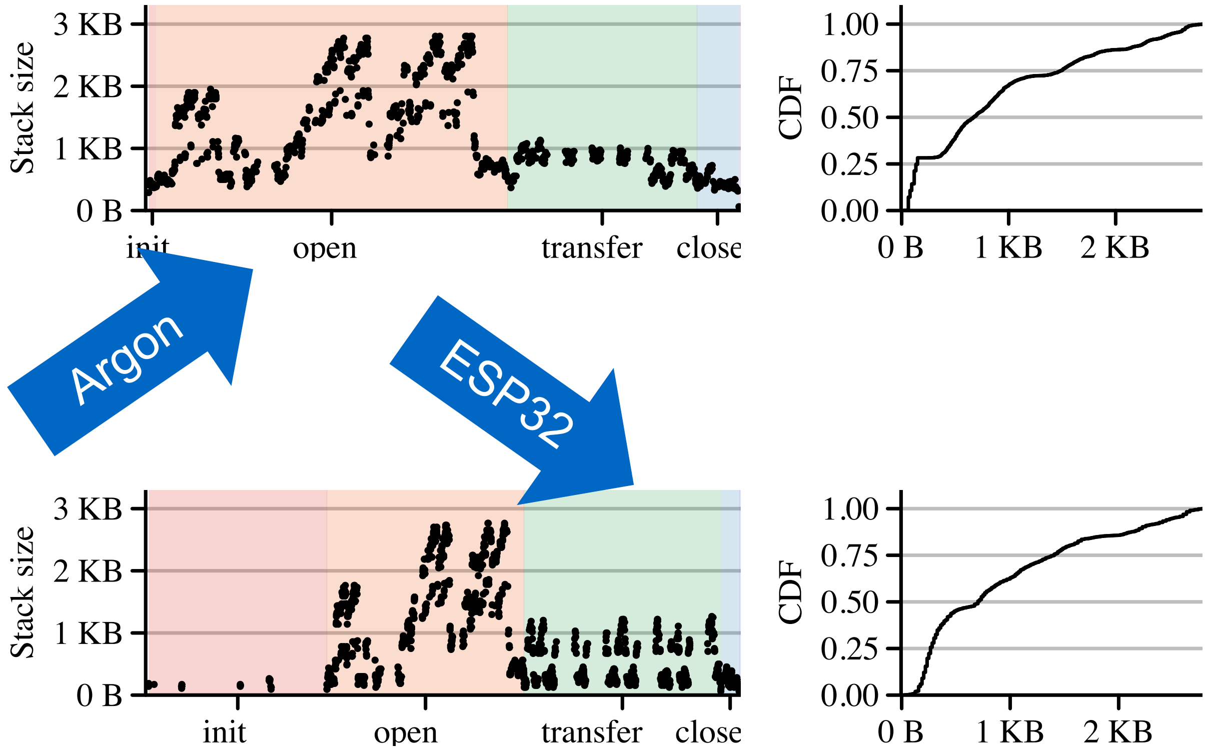


Measurements

Stack and heap usage

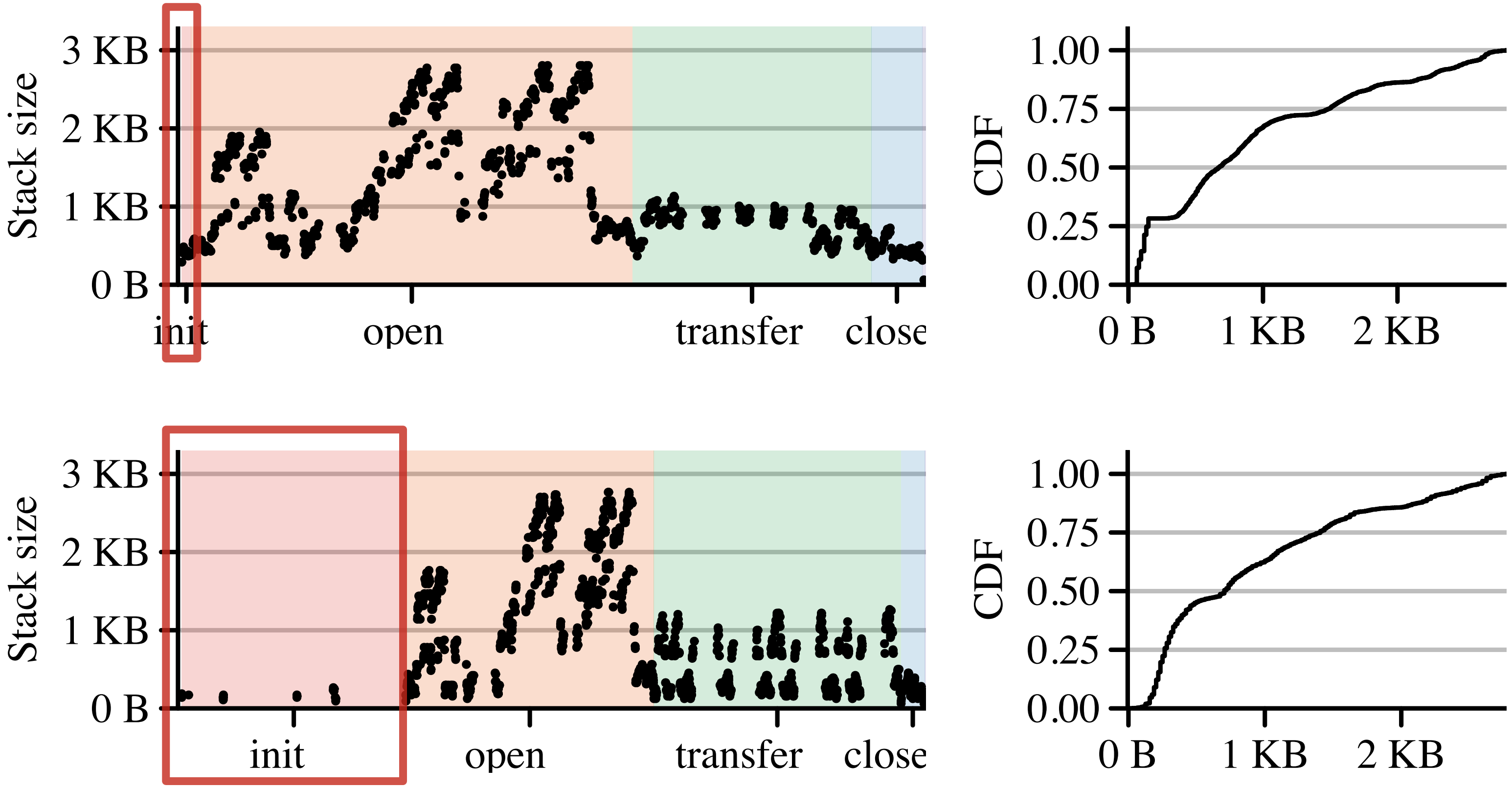
Stack and heap usage

- **Instrumented binaries** to log stack and heap usage on function enter/exit
- cifra and micro-cc ***NOT*** instrumented
  - Too many small functions, too much log data
- Shown results are therefore **lower bounds**
  - Approximate the case *if* HW did crypto
- **Time units not shown** on purpose
  - Run takes tens of seconds due to 112.5Kb/s serial
- **Random 20%** of data points plotted to reduce overplotting



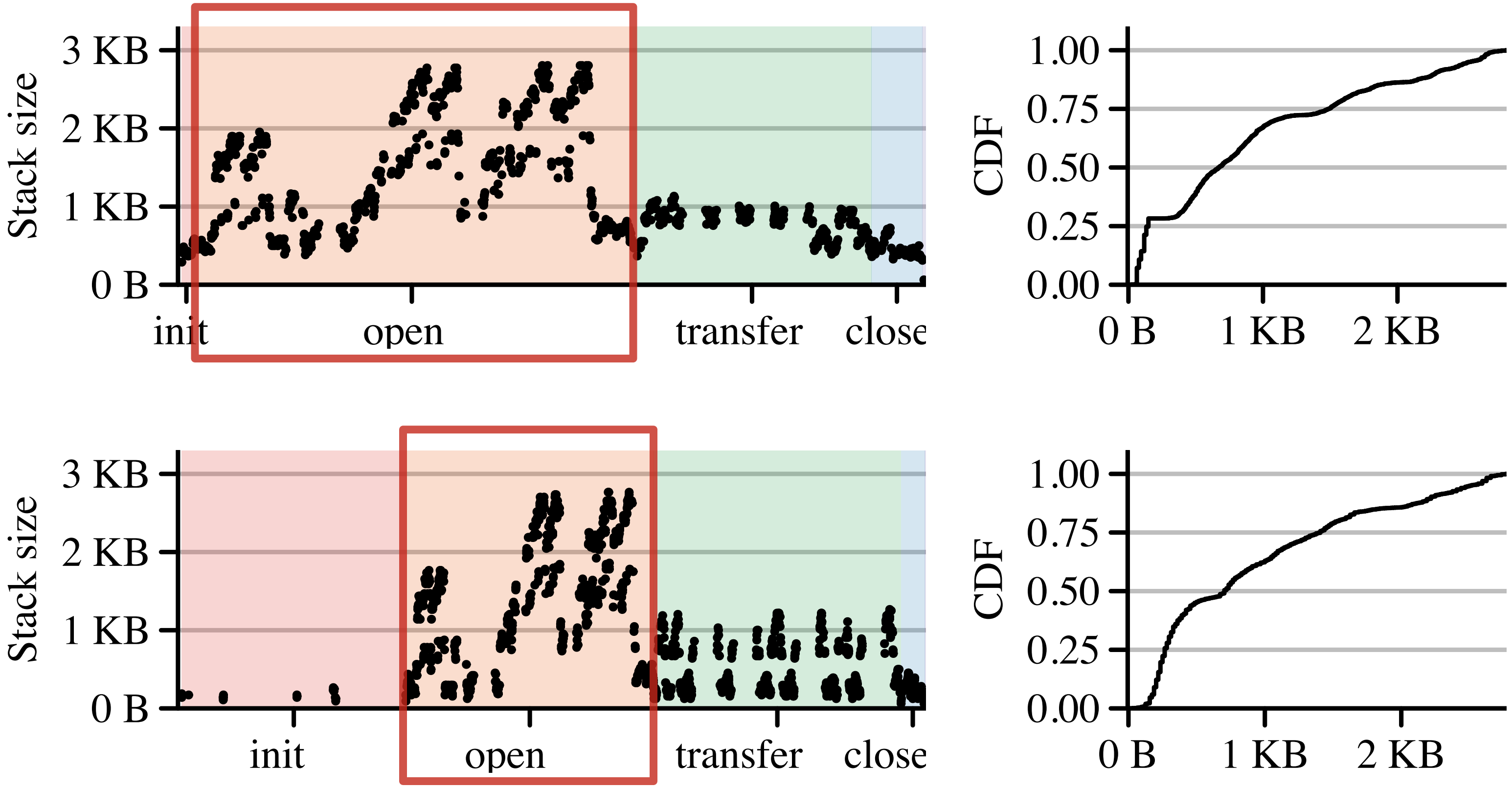
Stack usage: init phase

- Quant and Warpcore initialization
- On ESP32, includes WLAN association = longer duration
- Minimal stack usage,few 100s of B



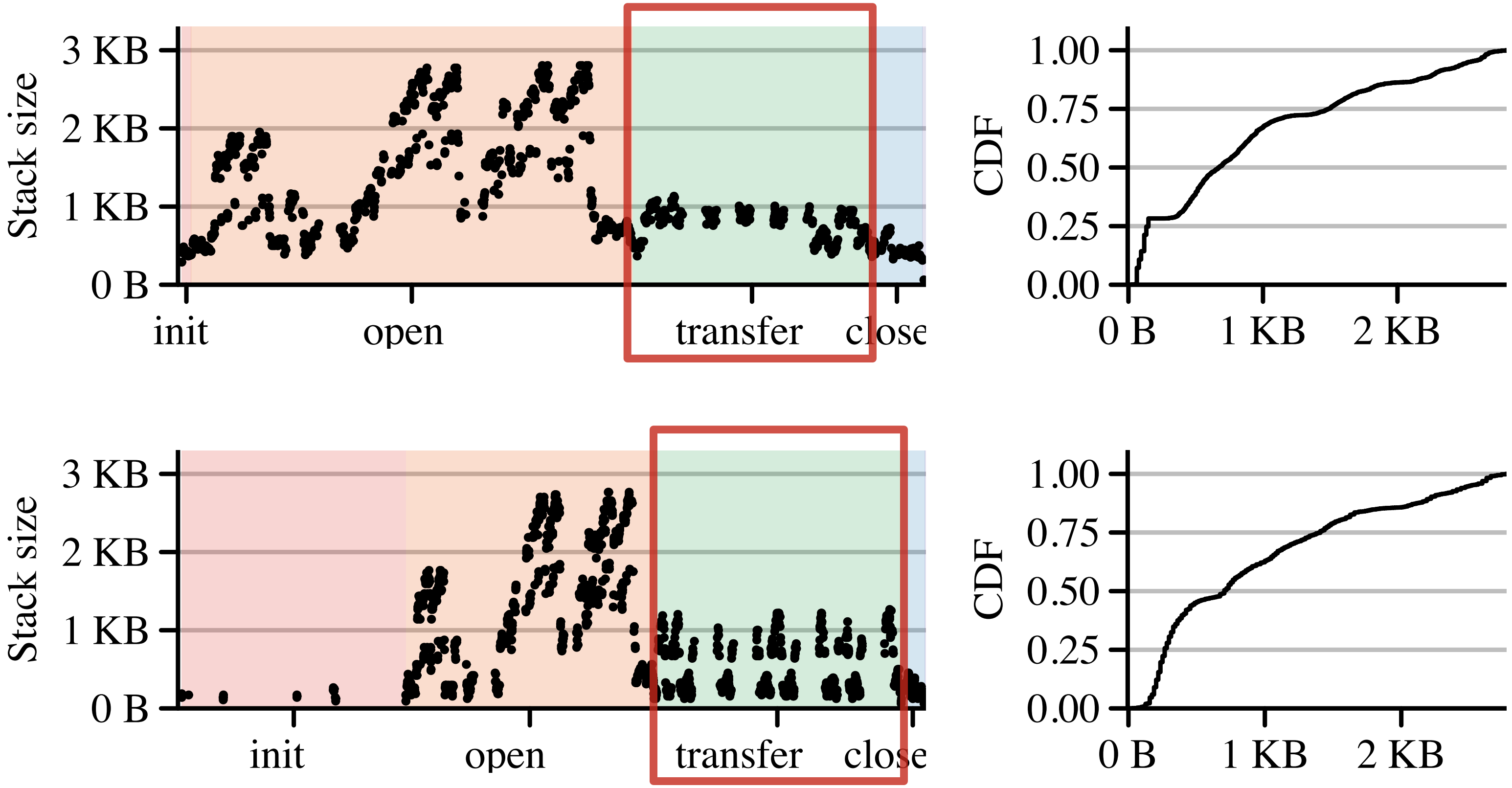
Stack usage: open phase

- Open connection to server
- **Public key crypto** as part of handshake
- **Stack usage peaks** at almost 3 KB
- **Not great** for IoT usage
  - 1 KB RIOT stack default
  - 6 KB Device OS stack default
- Optimizations needed
  - picotls uses stack-allocated buffers



Stack usage: transfer phase

- RX data from server
- **Symmetric crypto**
- **Stack usage is lower** at around 1 KB
- **Still not super-great** for IoT
- Optimizations needed



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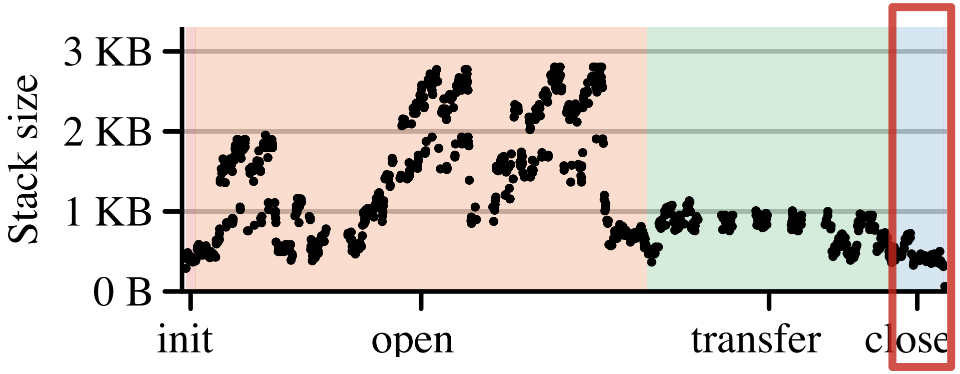
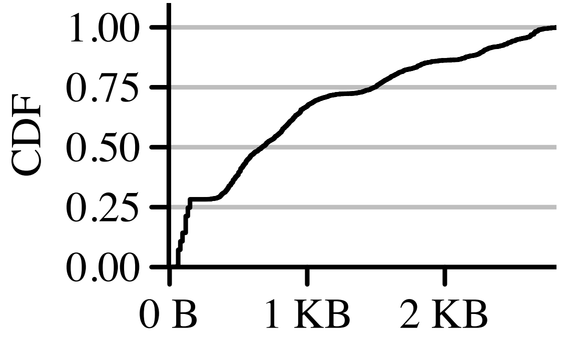
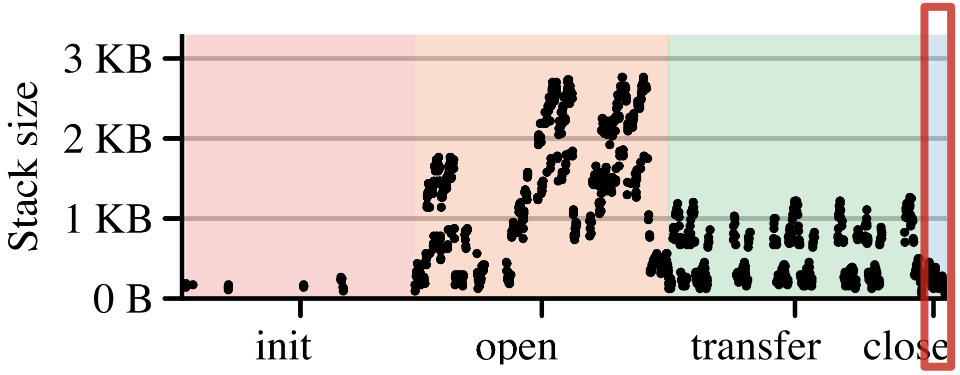
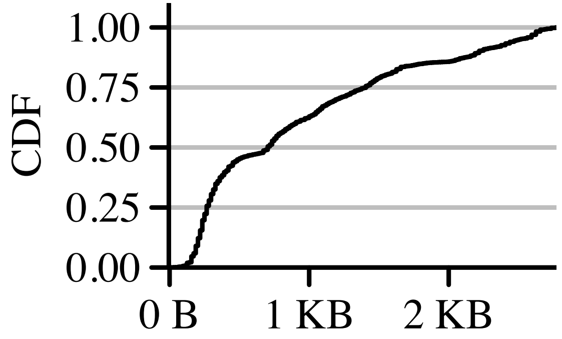
Stack usage: close phase

- Close connection with server and de-init
- **Stack usage dropping** down to initial values





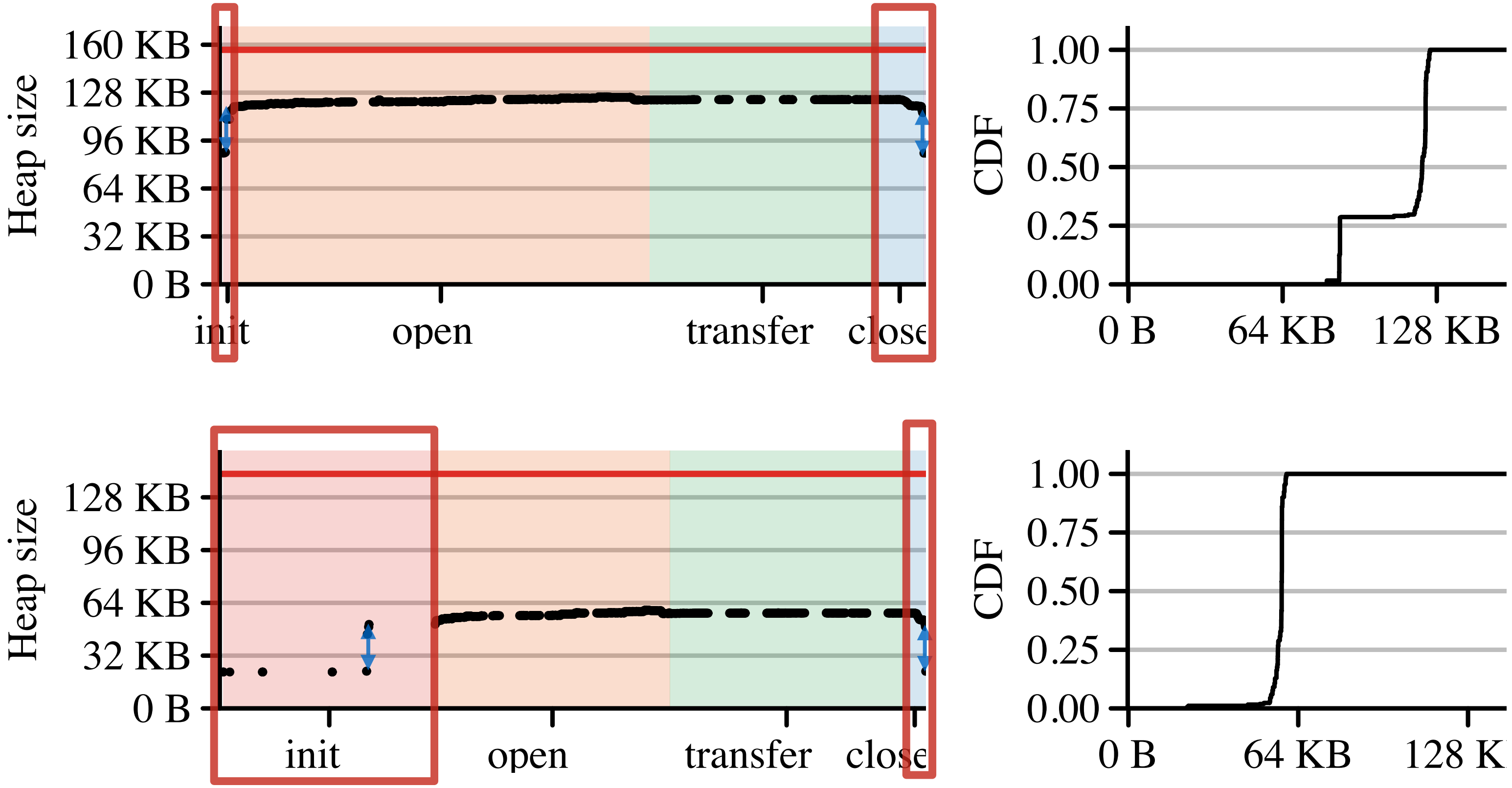




- Overall, unfortunately, **peak stack usage** is what matters

Heap usage

- **Heap usage jumps** on allocation/deallocation of packet buffers
- 15 buffers @ 1500 B each
- Baseline heap usage on Argon much higher
  - DeviceOS executing in background



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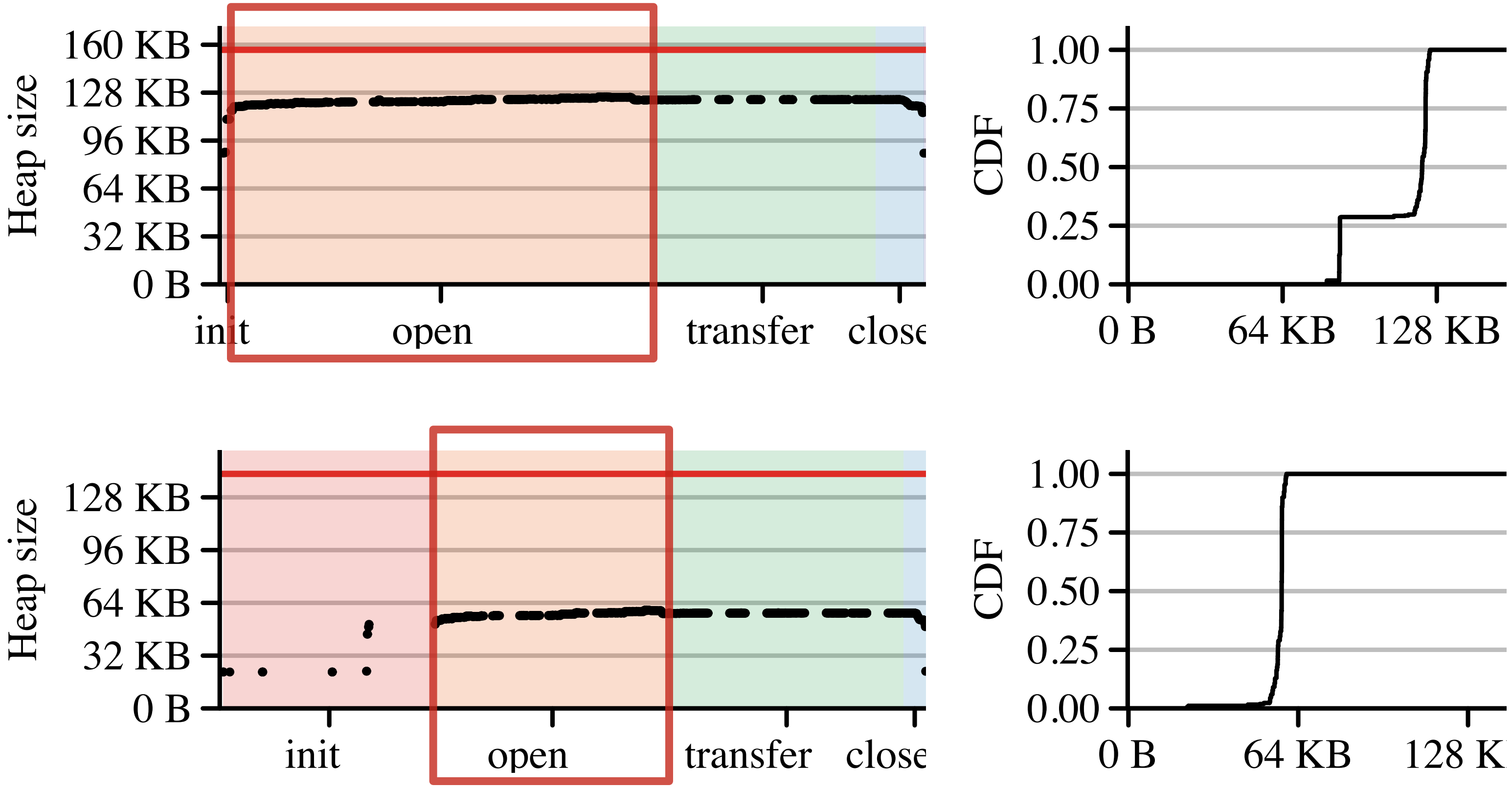
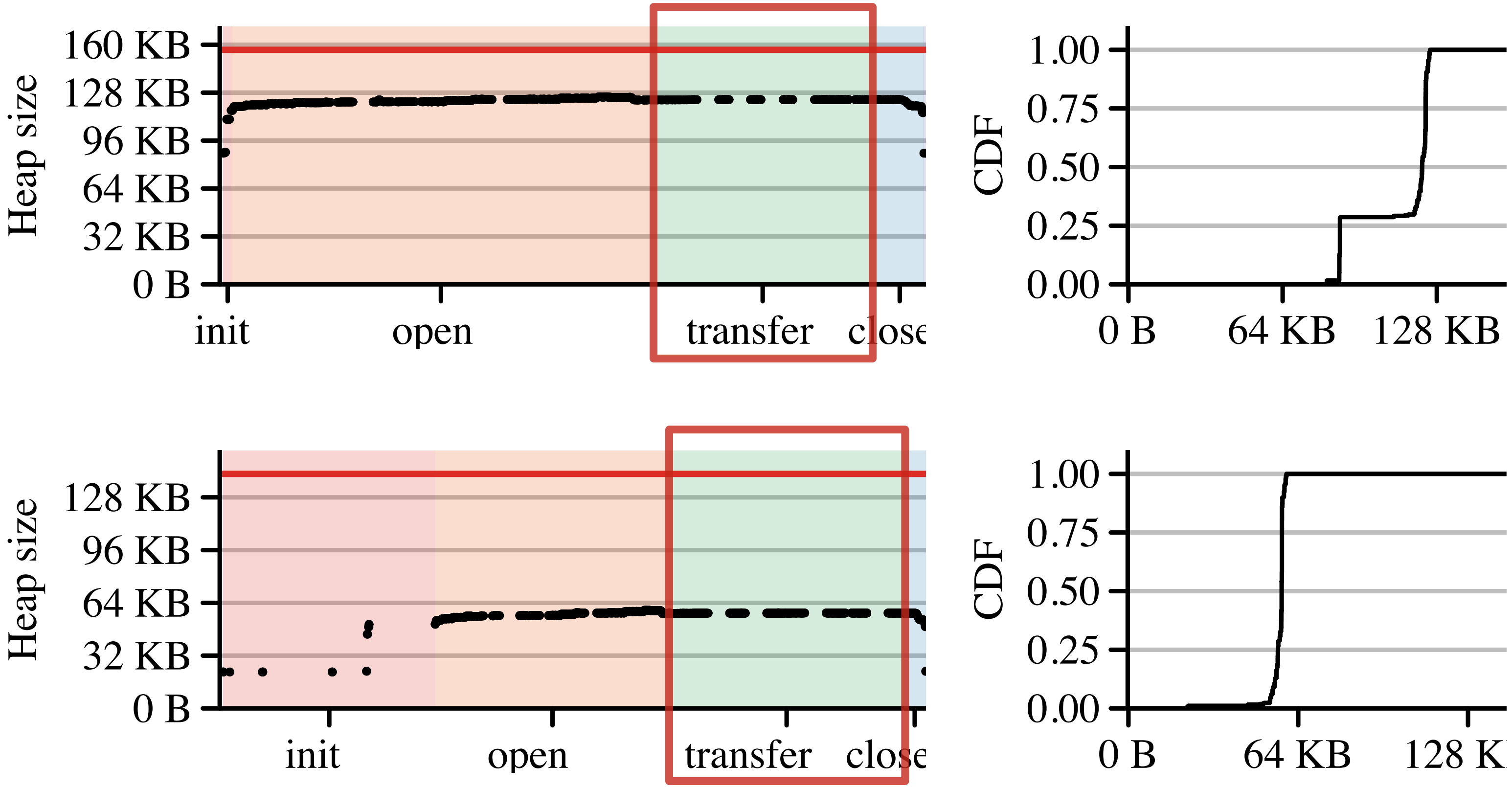
Heap usage

- During open phase, **slight increase in heap**
- Allocation of additional per-connection dynamic state



Heap usage

- **Flat heap usage** during transfer phase
- Nice!

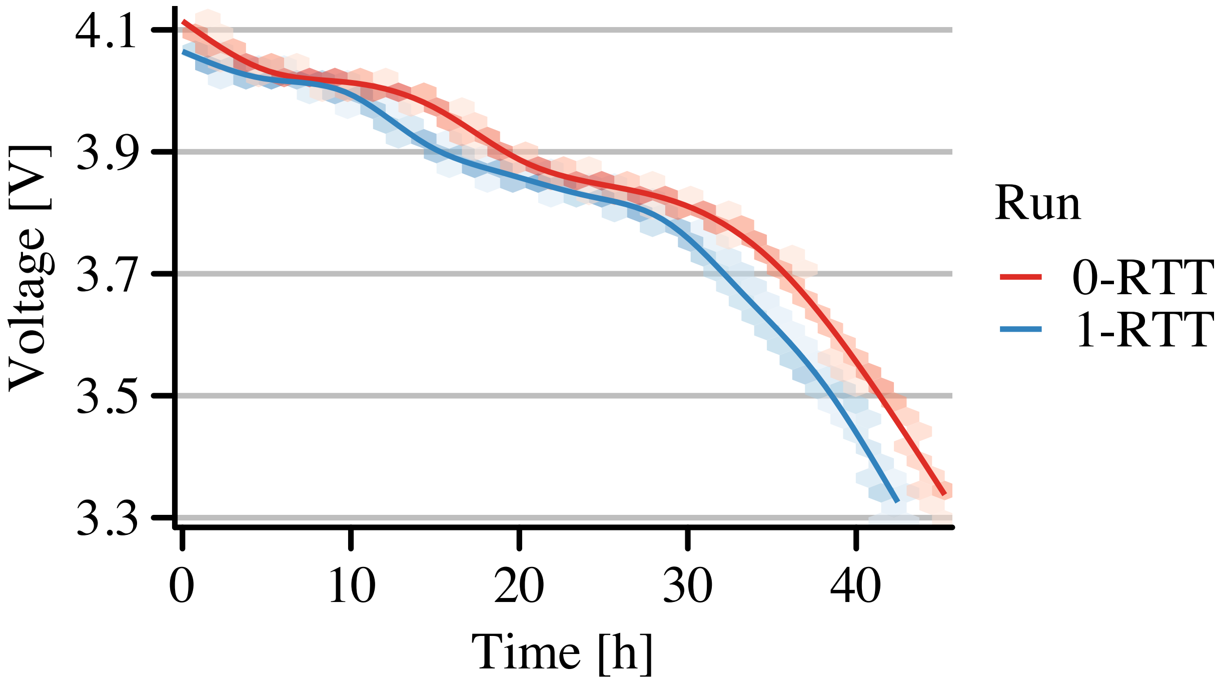


Measurements

Energy and performance

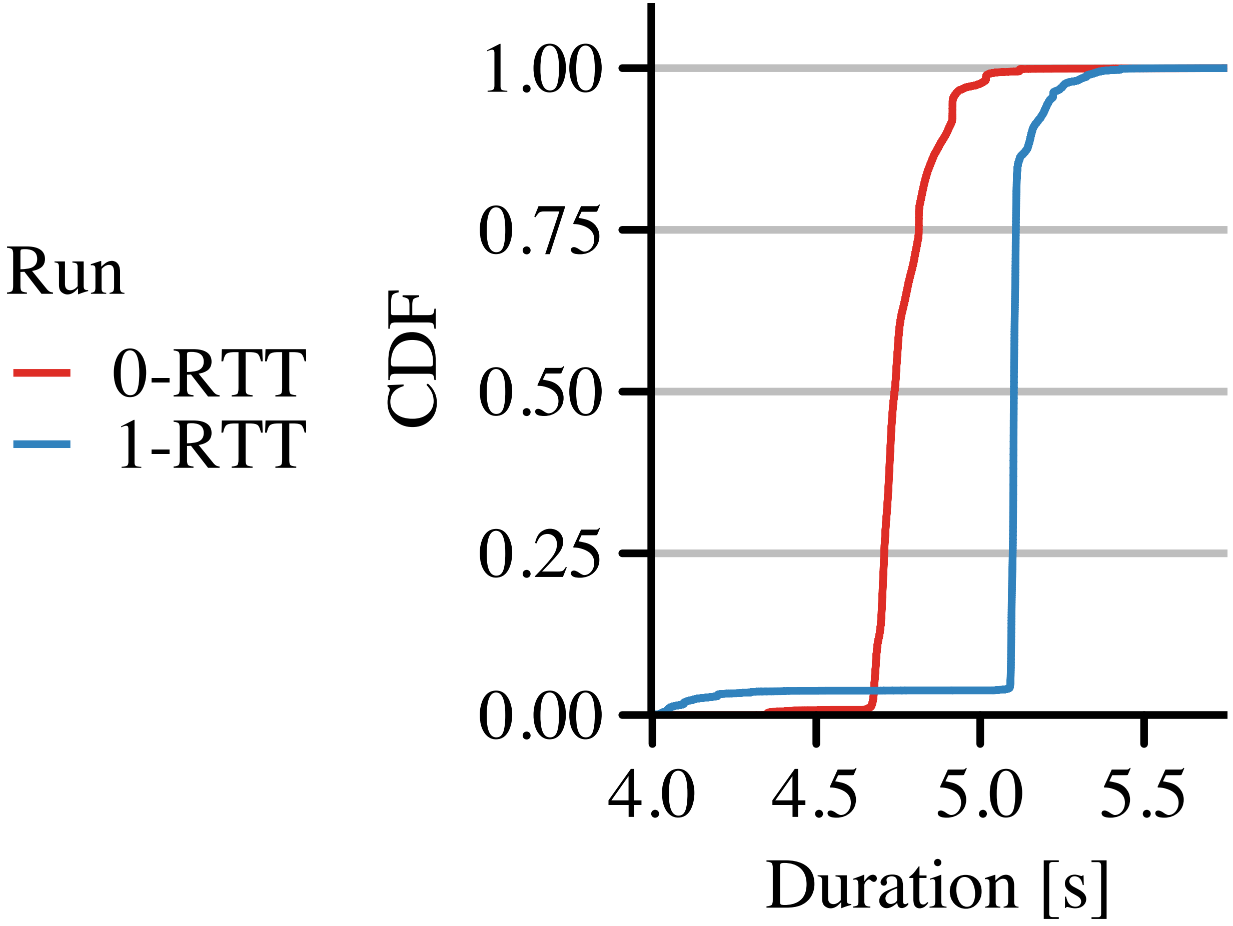
Energy measurements

- Argon with 2000 mAh 3.7 V LiPo battery
- **Two runs** after full charges
  - **Only 1-RTT** connections
  - (Initial 1-RTT followed by) **only 0-RTT** connections
- Ran for ~2.5 days non-stop
  - 29,338 1-RTT connections (~0.90 J/conn)
  - 31,844 0-RTT connections (~0.83 J/conn)
- **Very preliminary!**
  - Argon-internal voltage reporting is coarse
  - Single run only
  - Hesitant to draw conclusions



Performance measurements

- Data from the same runs used for energy measurements
- Median 1-RTT connection took 5.10 s
- Median 0-RTT connection took 4.74 s
- Open questions
  - Why does 0-RTT show more of a slope?
  - Why is 1-RTT sometimes faster? (Loss?)



Future work

Lots and lots

Future work

Measurements

- Measure **data upload**
- **Vary parameters** of measurement
  - Object sizes, streams, connections, etc.
- **Compare** against other protocols
  - TCP, TLS/TCP, CoAP, MQTT, etc.
- **Compare** different IoT boards
- More accurate **energy measurements**

Implementation

- Add **H3** binding & measure
- Make **picotls** not use stack buffers
- **Better data structures** w/less heap churn
- Use **HW crypto** (performance & energy)
- **Drop 0-RTT** to shrink code size?
- IP over **BLE or 802.15.4** instead of WLAN
  - WLAN on ESP32 is 115 KB (45% of OS size)
- Can we scale down to **16-bit controllers**?

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Thank you

Questions later?
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