



## “Flexible Channel Estimation for 3GPP 5G IoT on a Vector Digital Signal Processor”

- *Generalisation of the moving average-based channel estimation and its mapping onto appropriately sized programmable platforms for 5G Release 17 IoT workloads, including the newly introduced RedCap.*
- *Identified workloads and requirements for channel estimation across all IoT specification.*
- *Devised an algorithmic approach that utilises flexibility of a programmable platform to provide robust approximate MMSE channel estimation quality using suboptimal moving average variants suitable for IoT, based on the best MSE performance criteria algorithm switching.*
- *Designed, implemented and measured denoising subkernels and the complete 5G IoT compatible channel estimation on 3 platforms, 32-bit RISC reference, vDSP128 and vDSP512 to cost effectively support IoT workloads.*
- *Processor SIMD architecture recommendation for each of the specified standards.*



# Motivation: Introduction of RedCap for 3GPP 5G IoT

- NR Reduced Capability (RedCap/REDCAP/NR-Lite/NR-Light) to cover applications in the m7nT10 .

3GPP Release 17 for 5G IoT  
(NB-IoT, Cat-M, RedCap)



Requirements  
and Workloads?

Algorithmic  
Approaches?

Suitable HW  
Platforms?

# Workload, Platforms, Algorithms

# Algorithmic Optimisation and 32-bit RISC Implementation

Further Algorithmic Optimisations:

- SMA – i) *mpy* instead of *div* ii) *discussion on less cycles of mac vs more cycles of add*
- EMA – i) *instead of (1-*

**SMA**

$$\tilde{H}(k, l) = \frac{1}{N_1 + N_2 + 1} \sum_{i=l-N_1}^{l+N_2} \hat{H}(k, i)$$

↓

$$\tilde{H}(k, l) = \alpha \sum_{i=l-N_2}^{l+N_2} \hat{H}(k, l+i) = \sum_{i=l-N_2}^{l+N_2} \alpha \cdot \hat{H}(k, l+i)$$

**EMA**

$$\tilde{H}(k, l) = \alpha \tilde{H}(k, l) + (1-\alpha) \hat{H}(k, l-1)$$

↓

$$\tilde{H}(k, l) = \alpha \tilde{H}(k, l) + \beta \hat{H}(k, l-1)$$

Operations [1/ms]:

- See TABLE IV (352x more than prior art Cat-M)

TABLE IV  
NUMBER OF OPERATIONS.

| Workload | Pilots [1/ms] | Operations [1/ms] |     | Filtering Axis |
|----------|---------------|-------------------|-----|----------------|
|          |               | SMA               | EMA |                |
| 1        | 4             | 24                | 8   | one axis       |
| 2        | 8             | 48                | 16  | one axis       |
| 3        | 12            | 72                | 24  | one axis       |
| 4        | 16            | 96                | 32  | one axis       |
| 5        | 20            | 120               | 40  | one axis       |
| 6        | 24            | 144               | 48  | one axis       |
| 7        | 28            | 168               | 56  | one axis       |
| 8        | 32            | 192               | 64  | one axis       |
| 9        | 36            | 216               | 72  | one axis       |
| 10       | 40            | 240               | 80  | one axis       |
| 11       | 44            | 264               | 88  | one axis       |
| 12       | 48            | 288               | 96  | one axis       |
| 13       | 52            | 312               | 104 | one axis       |
| 14       | 56            | 336               | 112 | one axis       |
| 15       | 60            | 360               | 120 | one axis       |
| 16       | 64            | 384               | 128 | one axis       |
| 17       | 68            | 408               | 136 | one axis       |
| 18       | 72            | 432               | 144 | one axis       |
| 19       | 76            | 456               | 152 | one axis       |
| 20       | 80            | 480               | 160 | one axis       |
| 21       | 84            | 504               | 168 | one axis       |
| 22       | 88            | 528               | 176 | one axis       |
| 23       | 92            | 552               | 184 | one axis       |
| 24       | 96            | 576               | 192 | one axis       |
| 25       | 100           | 600               | 200 | one axis       |
| 26       | 104           | 624               | 208 | one axis       |
| 27       | 108           | 648               | 216 | one axis       |
| 28       | 112           | 672               | 224 | one axis       |
| 29       | 116           | 696               | 232 | one axis       |
| 30       | 120           | 720               | 240 | one axis       |
| 31       | 124           | 744               | 248 | one axis       |
| 32       | 128           | 768               | 256 | one axis       |
| 33       | 132           | 792               | 264 | one axis       |
| 34       | 136           | 816               | 272 | one axis       |
| 35       | 140           | 840               | 280 | one axis       |
| 36       | 144           | 864               | 288 | one axis       |
| 37       | 148           | 888               | 296 | one axis       |
| 38       | 152           | 912               | 304 | one axis       |
| 39       | 156           | 936               | 312 | one axis       |
| 40       | 160           | 960               | 320 | one axis       |
| 41       | 164           | 984               | 328 | one axis       |
| 42       | 168           | 1008              | 336 | one axis       |
| 43       | 172           | 1032              | 344 | one axis       |
| 44       | 176           | 1056              | 352 | one axis       |
| 45       | 180           | 1080              | 360 | one axis       |
| 46       | 184           | 1104              | 368 | one axis       |
| 47       | 188           | 1128              | 376 | one axis       |
| 48       | 192           | 1152              | 384 | one axis       |
| 49       | 196           | 1176              | 392 | one axis       |
| 50       | 200           | 1200              | 400 | one axis       |
| 51       | 204           | 1224              | 408 | one axis       |
| 52       | 208           | 1248              | 416 | one axis       |
| 53       | 212           | 1272              | 424 | one axis       |
| 54       | 216           | 1296              | 432 | one axis       |
| 55       | 220           | 1320              | 440 | one axis       |
| 56       | 224           | 1344              | 448 | one axis       |
| 57       | 228           | 1368              | 456 | one axis       |
| 58       | 232           | 1392              | 464 | one axis       |
| 59       | 236           | 1416              | 472 | one axis       |
| 60       | 240           | 1440              | 480 | one axis       |
| 61       | 244           | 1464              | 488 | one axis       |
| 62       | 248           | 1488              | 496 | one axis       |
| 63       | 252           | 1512              | 504 | one axis       |
| 64       | 256           | 1536              | 512 | one axis       |
| 65       | 260           | 1560              | 520 | one axis       |
| 66       | 264           | 1584              | 528 | one axis       |
| 67       | 268           | 1608              | 536 | one axis       |
| 68       | 272           | 1632              | 544 | one axis       |
| 69       | 276           | 1656              | 552 | one axis       |
| 70       | 280           | 1680              | 560 | one axis       |
| 71       | 284           | 1704              | 568 | one axis       |
| 72       | 288           | 1728              | 576 | one axis       |
| 73       | 292           | 1752              | 584 | one axis       |
| 74       | 296           | 1776              | 592 | one axis       |
| 75       | 300           | 1800              | 600 | one axis       |
| 76       | 304           | 1824              | 608 | one axis       |
| 77       | 308           | 1848              | 616 | one axis       |
| 78       | 312           | 1872              | 624 | one axis       |
| 79       | 316           | 1896              | 632 | one axis       |
| 80       | 320           | 1920              | 640 | one axis       |
| 81       | 324           | 1944              | 648 | one axis       |
| 82       | 328           | 1968              | 656 | one axis       |
| 83       | 332           | 1992              | 664 | one axis       |
| 84       | 336           | 2016              | 672 | one axis       |
| 85       | 340           | 2040              | 680 | one axis       |
| 86       | 344           | 2064              | 688 | one axis       |
| 87       | 348           | 2088              | 696 | one axis       |
| 88       | 352           | 2112              | 704 | one axis       |
| 89       | 356           | 2136              | 712 | one axis       |
| 90       | 360           | 2160              | 720 | one axis       |
| 91       | 364           | 2184              | 728 | one axis       |
| 92       | 368           | 2208              | 736 | one axis       |
| 93       | 372           | 2232              | 744 | one axis       |
| 94       | 376           | 2256              | 752 | one axis       |
| 95       | 380           | 2280              | 760 | one axis       |
| 96       | 384           | 2304              | 768 | one axis       |
| 97       | 388           | 2328              | 776 | one axis       |
| 98       | 392           | 2352              | 784 | one axis       |
| 99       | 396           | 2376              | 792 | one axis       |
| 100      | 400           | 2400              | 800 | one axis       |

Pseudo Code of Optimised Equations:

```

Algorithm 1: Moving Average in the SMA Form
input : Channel measurement  $\hat{H}$  and filter coefficient  $\alpha$ 
output : Filtered channel measurement  $\tilde{H}$ 
// Data register  $w$ 
// MAC register  $w_1$ 
for  $j \leftarrow 0$  to  $K-1$  do
  for  $k \leftarrow 0$  to  $N-1$  do
     $w_1 \leftarrow \alpha \hat{H}(k, j) + (1-\alpha) w_1$ 
  end
   $\tilde{H}(j) \leftarrow w_1$ 
end

Algorithm 2: Moving Average in the EMA Form
input : Channel measurement  $\hat{H}$  and filter coefficients  $\alpha, \beta$ 
output : Filtered channel measurement  $\tilde{H}$ 
// Data register  $w$ 
// ACC register  $w_1$ 
 $w_1 \leftarrow 0$ 
for  $k \leftarrow 0$  to  $K-1$  do
  for  $l \leftarrow 0$  to  $N-1$  do
     $w_1 \leftarrow \alpha \hat{H}(k, l) + \beta w_1$ 
  end
   $\tilde{H}(k) \leftarrow w_1$ 
end
    
```

32-bit reference Implementation:

- Cycles [1/ms] -> Frequency [kHz]
- i) 25 MHz for just FR2 RedCap denoising is unacceptable, a SIMD solution is needed. ii) NB-IoT OK.

TABLE V  
32-BIT SCALAR REFERENCE REQUIRED CLOCK FREQUENCY AND MINIMUM UNIT UTILISATION

| Workload | Frequency [MHz] | Utilisation [%] |
|----------|-----------------|-----------------|
| EMA      | 106             | 34              |
| SMA      | 76              | 24              |
| EMA      | 63              | 20              |
| SMA      | 48              | 15              |
| EMA      | 34              | 11              |
| SMA      | 25              | 8               |
| EMA      | 18              | 6               |
| SMA      | 14              | 4               |
| EMA      | 10              | 3               |
| SMA      | 7               | 2               |
| EMA      | 5               | 1               |
| SMA      | 4               | 1               |

Ops/cycles go up with higher workloads due to relatively smaller loop overhead and pipeline depth impact

VODAFONE CHAIR

VODAFONE CHAIR

# Results: Key Contributions

## Algorithm:

- *Moving Average filter variations offer good MSE performance and low computational cost – good for IoT*
- *MSE performance near optimal (MMSE) with SW alg. switching*
- *SW Switching is easy on a flexible, programmable platforms*

| Algorithm    | Moving Average based Channel Estimation |                       |             |                 |             |                 |
|--------------|---|-----------------------|-------------|-----------------|-------------|-----------------|
| Architecture | 32-bit scalar                           |                       | vDSP128     |                 | vDSP512     |                 |
| Metric       | Req. Clock                              | Arithmetic Ops/Cycles | Req. Clock  | SIMD Efficiency | Req. Clock  | SIMD Efficiency |
|              | [MHz]                                   | [%]                   | [MHz]       | [%]             | [MHz]       | [%]             |
| NB-IoT       | <b>0.25</b>                             | <b>89</b>             | 0.08        | 67              | 0.04        | 33              |
| Cat-M        | <b>1.28</b>                             | <b>97.8</b>           | <b>0.34</b> | <b>92</b>       | 0.11        | 74              |
| FR1 RedCap   | 25.9                                    | 99.89                 | <b>6.5</b>  | <b>99.48</b>    | <b>1.65</b> | <b>97.9</b>     |
| FR2 RedCap   | 128.9                                   | 99.98                 | 32.4        | 99.89           | <b>8.09</b> | <b>99.58</b>    |

| Standard              | NB-IoT        | Cat-M                    | FR1 RedCap                | FR2 RedCap     |
|-----------------------|---------------|--------------------------|---------------------------|----------------|
| Suitable Architecture | <b>32-bit</b> | <b>32-bit to 128-bit</b> | <b>128-bit to 512-bit</b> | <b>512-bit</b> |