GMR-1 Speech codec

GMR-1 Speech codec

The problem

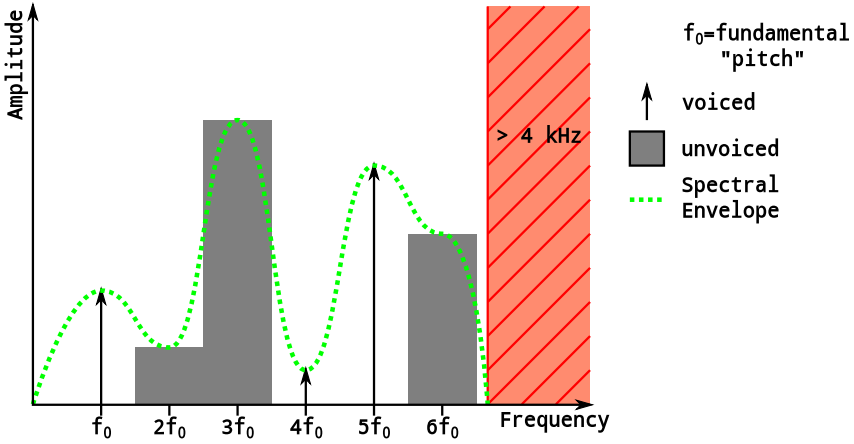
- AMBE: Advanced Multi-Band Excitation
- Not documented in the standard
  - Barely a high level description
  - No reference code
- Proprietary codec by *DVSI Inc.*
  - Not supported by their "cheap" hardware USB decoder
  - Cheapest hardware is the NET-2000 appliance (2kEUR)
- But :
  - `mbelib`: Code for other documented IMBE/AMBE variants (P25)
  - Implemented in SO2510 phone DSP (`TI C55x`)

AMBE Codec
Description

- Highly specialized for voice (vocoder)
- Divides speech in small segments
  - For GMR-1: 20 ms frames subdivided into co-quantized 10 ms sub-frames
- Represent each speech (sub)frame as a set of parameters
  - f_0 : Fundamental frequency *(pitch)*
  - G : Gain *(volume)*
  - Voiced / Unvoiced decision (per band)
  - Spectral Magnitudes
- Decoding can be summarized as 3 steps:
  - **Unpacking**: Unpack the raw frame bits into quantized parameters
  - **De-Quantization**: From quantized parameters to actual values
  - **Synthesis**: From the parameters set to actual audio

AMBE Codec

Synthesis



AMBE Reversing

DSP Code analysis

- Target: SO-2510 phone
- Codec has to be in the DSP, nowhere else it could be !
- DSP firmware extracted from firmware update package
  - Supported by IDA
- But where ?
  - 250k binary blob
  - No strings
  - Obscure `TI C55x` assembly
- Dieter Spaar to the rescue !
  - Identified entry points for encode/decode functions
  - Look for Audio DMA / Interrupts
  - Search for constants
  - Stack Switching

AMBE Reversing
Simulator

- TI Code Composer Studio - Simulator
  - Accurately simulates supported DSP
  - Arbitrary memory layout
  - fread()/fwrite() from host
  - Tracing of all memory access
  - Windows only :(
- Use the original firmware to decompress audio for us
  - DSP dump converted to a valid COFF .OBJ file for linking
  - Custom linker script
  - Simple main() that fread() frames and fwrite() audio
- Success !
  - It took quite a few tries, lots of traps
  - But it works and we get audio out
  - Slow (not real-time) and not practical though

AMBE Reversing

Hardware

- Real HW would be faster and more convenient. But :
  - Code has to run at the physical address it has been linked for
  - OMAP has a DSP MMU, but standalone DSP don't
  - Need a cheap board with a compatible memory map
- Dieter found one with SDRAM where needed and Ethernet
  - Success ! About 16x faster than real-time
  - SDRAM is not fast, relocate some data tables to SRAM
- I indented to buy the same board
  - But in my haste ... I ordered the wrong one ... ***facepalm***
  - No SDRAM, more SRAM, but at the wrong physical address
  - Easy, just relocate the code ! Can't be that hard, right ?
  - Use `IDAPython` + simulator trace mode
  - Success !

AMBE Reversing
Software

- Hardware USB decoder is nice, but not enough
- Decompression process:
  - **Unpacking**
    - Early, simple bit manipulation, easy to follow
  - **Dequantization**
    - Easily 95% of the work
    - Hard to follow fixed point math in DSP assembly
  - **Synthesis**
    - Started by just re-using `mbelib` code
    - Then rewrote using P25 specs and some guessing
- Resulting PoC/reference code in GIT
  - Not same audio quality as the original, but perfectly intelligible

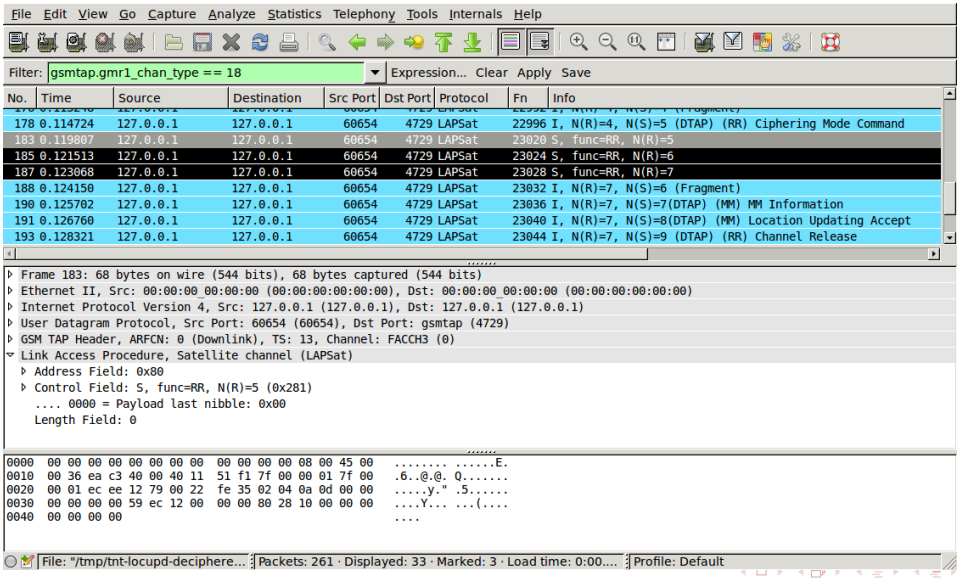
```
amar    *+AR0(#857h)
call    sub_103540
mov     *AR6(#100h), AR1
btst    @0, AR1, TC1
mov     #0, T2
xccpart !TC1
bcc     loc_10B148, !TC1
amar    *AR7, XAR0
amar    *AR5, XAR1
|| mov T2, T0
call    sub_109EC8
mov     T0, T2


amar    *AR5, XAR3
amar    *AR5, XAR4
amar    *+AR3(#684h)
amar    *AR3, XAR2
amar    *+AR4(#684h)
amar    *AR5, XAR3
amar    *+AR3(#584h)
rpt     #0FFh
mov     *AR4+, *AR3+
mov     *AR5(#785h), AR1
mov     AR1, *AR5(#784h)
amar    *SP(#var_0), XAR3
|| rpt #0FFh
mov     *AR3+, *AR2+
add     #102h, mmap(@SP)
mov     T3, *AR5(#785h)
popboth XAR6
```

A better attack
Overview

- Based on the same A5/2 GSM attack
  - Don't do anything fancy, just tweak for A5-GMR-1
- Both known-plaintext and ciphertext-only variant
- Targets `FACCH3` control frames instead of `TCH3` voice frames
- `FACCH3` advantages :
  - Simpler modulation and better training sequence → less bit-errors
  - Predictable plaintext → known-plaintext attacks
  - Much more redudancy (more FEC) → less bursts needed for ciphertext-only attacks
  - Used to negotiate `TCH6`/`TCH9` channels → attack works for CSD/Fax

A better attack

Known plaintext



A better attack
Plaintext attack

- Goal is to describe cipher as a linear operation: $A \cdot x = b$
  - A = matrix describing cipher, x = internal state and b = cipher stream
  - Each row of A and b is a bit of the output
- Internal cipher state dependency on FN and Kc is linear
  - Possible to combine equations from different bursts at different FN
  - Can recover Kc from the state
- Non-linear elements:
  - Majority function: $\mathcal{M}(a, b, c) = a + b.c$
    - Introduces quadratic terms
    - Linearize by adding one new unknown for every possible quadratic term
    - 594 new unknowns
  - Irregular clocking depending on R4 value
    - R4 is 17 bits but one is forced to '1' at init. Small enough for brute force !
    - Assume a given value for R4
    - Repeat 65536 times

A better attack

R4 quick scan

- In $A_n \cdot x = b$, some equations are redundant
- We can get a parity-check matrix H_n such that $H_n \cdot b = \mathbf{0}$
- Those 65536 H_n matrices can be precomputed offline
- With a single matrix-multiply we can check if a given R4 value is even a possibility
  - If result is non-zero, we can skip that R4 value
  - If result is zero, then we try to solve the system
  - In practice, only a few R4 value ever matches

A better attack

Ciphertext only

- Channel coding operation: $m = d \cdot G + g$
- Let H be the parity-check matrix so that $H \cdot (m + g) = \mathbf{0}$
- Encryption operation: $y = m + b$
- H can be used to derive equations from the ciphertext y:

$$\begin{aligned} H \cdot (y + g) &= H \cdot (m + b + g) \\ &= H \cdot b + \underbrace{H \cdot (m + g)}_{\mathbf{0}} \\ &= H \cdot A \cdot x \end{aligned}$$

- The same R4 quick-scan technique can also be used here
- To get enough equations for a unique solutions, multiple frames are needed

A better attack
Results

- Known-plaintext variant
  - Requires between 4 and 8 bursts depending on alignement
  - Space: 50 Mb
  - Time: 500 ms
- Ciphertext-only variant
  - Requires 8 consecutive bursts belonging to 2 FACCH3 L2 frames
  - Space: 5 Gb
  - Time: 1 s

Final words

Future

- C-band
- Packet Data (GmPRS)
- Upper layers implementation
- CSN.1 and 04.008 code generators
- TX side

Help welcome :)

Other satellite phone systems

- We choose Thuraya because :
  - Visible from Europe
  - Cheapest sat phone on ebay
  - Specifications mostly available
- Don't think other are better without proof
  - Availability of commerical intercepts tend to say otherwise

Thanks

Thanks to anyone who contributed to this projects and related ones. Most notably:

- Dimitri "horizon" Stolnikov
- Dieter Spaar
- RUB team

Further reading

- GMR-1 in general
  - OsmocomGMR `http://gmr.osmocom.org/`
  - 28C3 talk `http://gmr.osmocom.org/trac/blog/28c3-recording`
  - GMR1 Specs `http://www.etsi.org/standards-search`
  - GSM Specs `http://webapp.etsi.org/key/queryform.asp`
- AMBE Codec
  - DVSI Inc. `http://www.dvsinc.com/`
- GMR-1 Cipher
  - RUB GMR page `http://gmr.crypto.rub.de/`
  - Paper `http://cryptome.org/gsm-crack-bbk.pdf`