Design and Hardware Evaluation of a Software-Defined Radio-Based Emergency Vehicle Pre-emption System

A decentralised 433 MHz beacon that triggers traffic-light pre-emption without roadside network or cellular infrastructure

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The problem, and the gap in existing pre-emption

1 **Congestion costs response time**

Ambulance delay in dense urban traffic translates directly into worse patient outcomes.

2 **Conventional EVP assumes infrastructure**

Commercial systems lean on roadside networks, cellular backhaul or central coordination.

3 **Nigerian intersections rarely have it**

Where that infrastructure is absent or unreliable, those systems cannot be deployed at all.

The question

Can a software-defined radio link, on its own, carry a pre-emption trigger reliably enough to change a traffic signal?

A beacon on the vehicle, a receiver at the intersection, and nothing in between. This paper builds that chain and measures it end to end.

433 MHz · GFSK · no network · no central control

System architecture

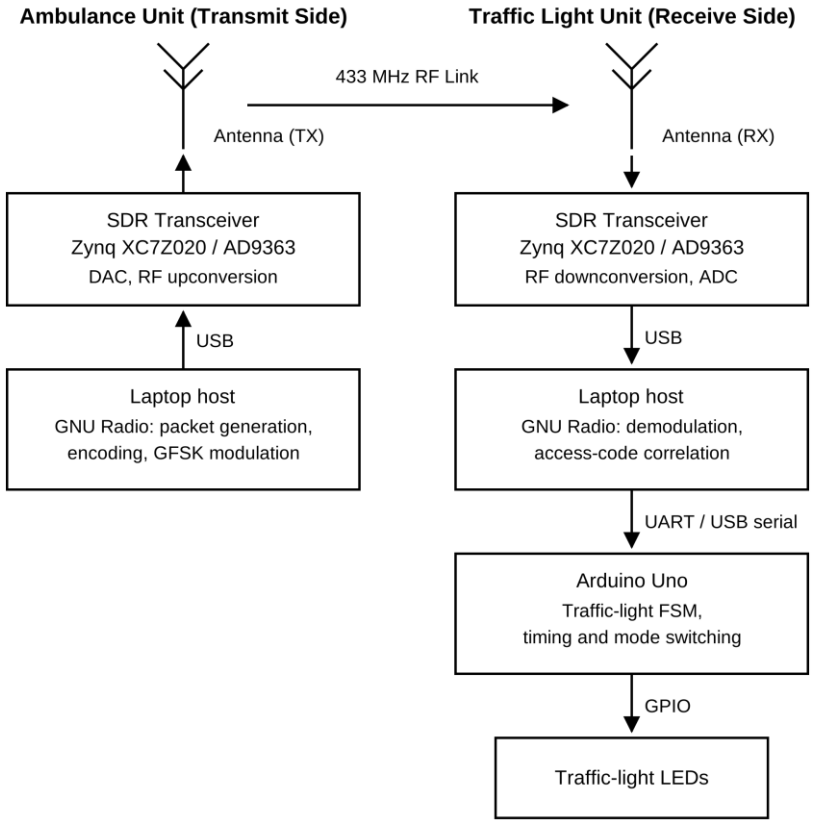


Fig. 1 of the paper

1 **Ambulance transmitter**

Zynq XC7Z020 + AD9363 on a laptop host; GFSK beacon at 433 MHz, 10 dB transmit attenuation, stock whip antenna.

2 **Intersection receiver**

Matched SDR demodulates and correlates against a known access code before accepting anything.

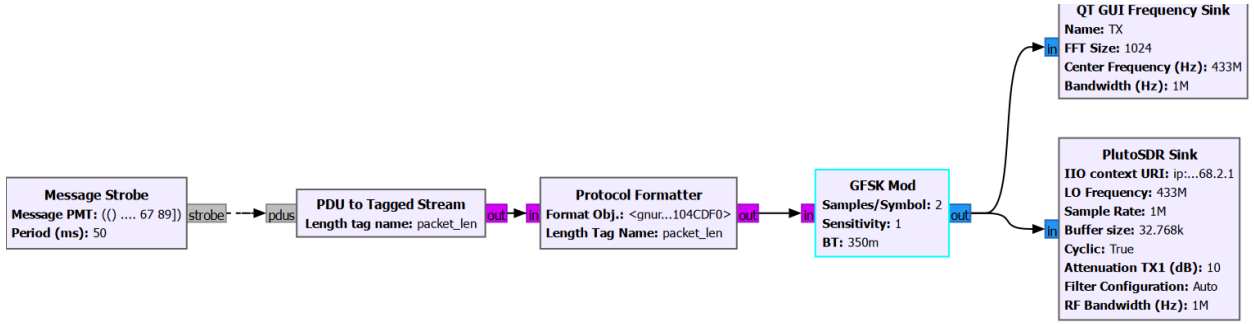
3 **Controller trigger**

A valid detection is passed over USB serial to an Arduino Uno as a single trigger byte.

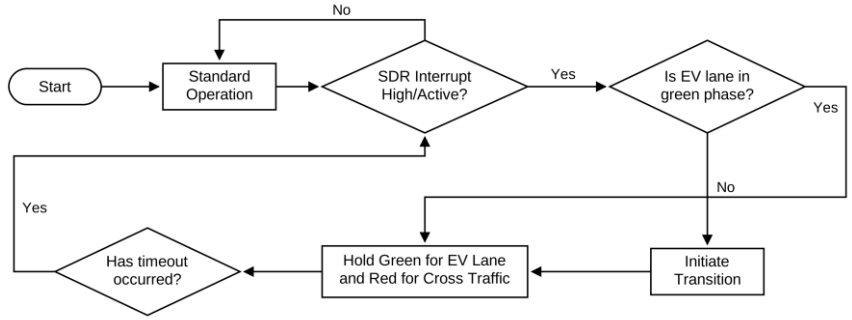
4 **Signal response**

The controller runs a two-lane finite-state machine and drives the signal heads.

Radio chain and controller logic



GNU Radio transmitter flowgraph



Controller finite-state machine

Modulation

GFSK, 2 samples/symbol, BT 0.35, 433 MHz carrier

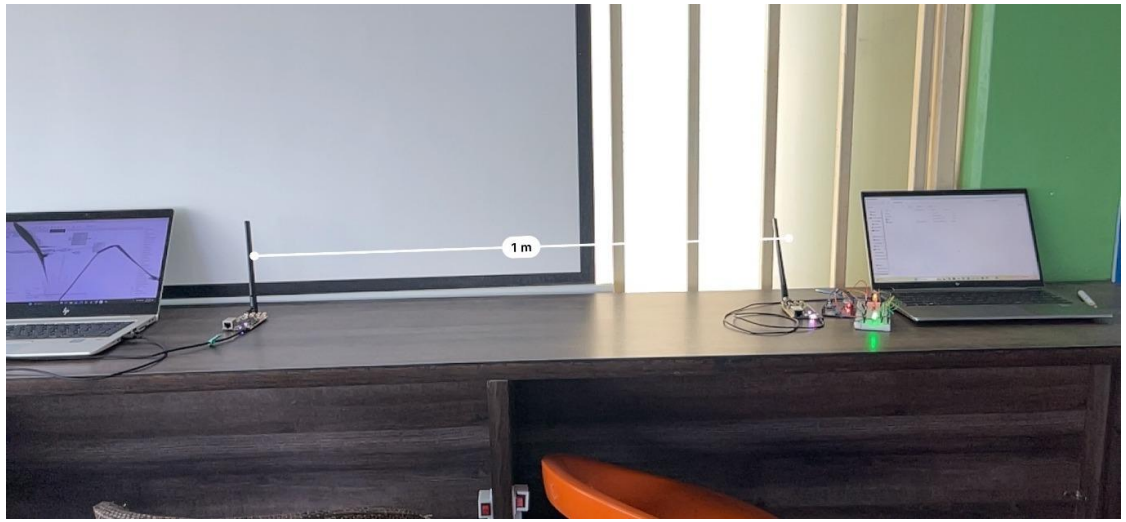
Admission

Access-code correlation at zero tolerated bit errors

Safety

Seven states; a full yellow interval always runs before the switch

Experimental method



Transmitter and receiver at 1 m separation

Test bench. Four separations from 1 to 10 m indoors, with a live controller and signal heads in the loop at every one.

RF margin

Peak and noise floor read from the frequency sink at four separations: 1, 2, 5 and 10 m.

Pre-emption outcome

Whether the controller actually changed state, recorded at each separation.

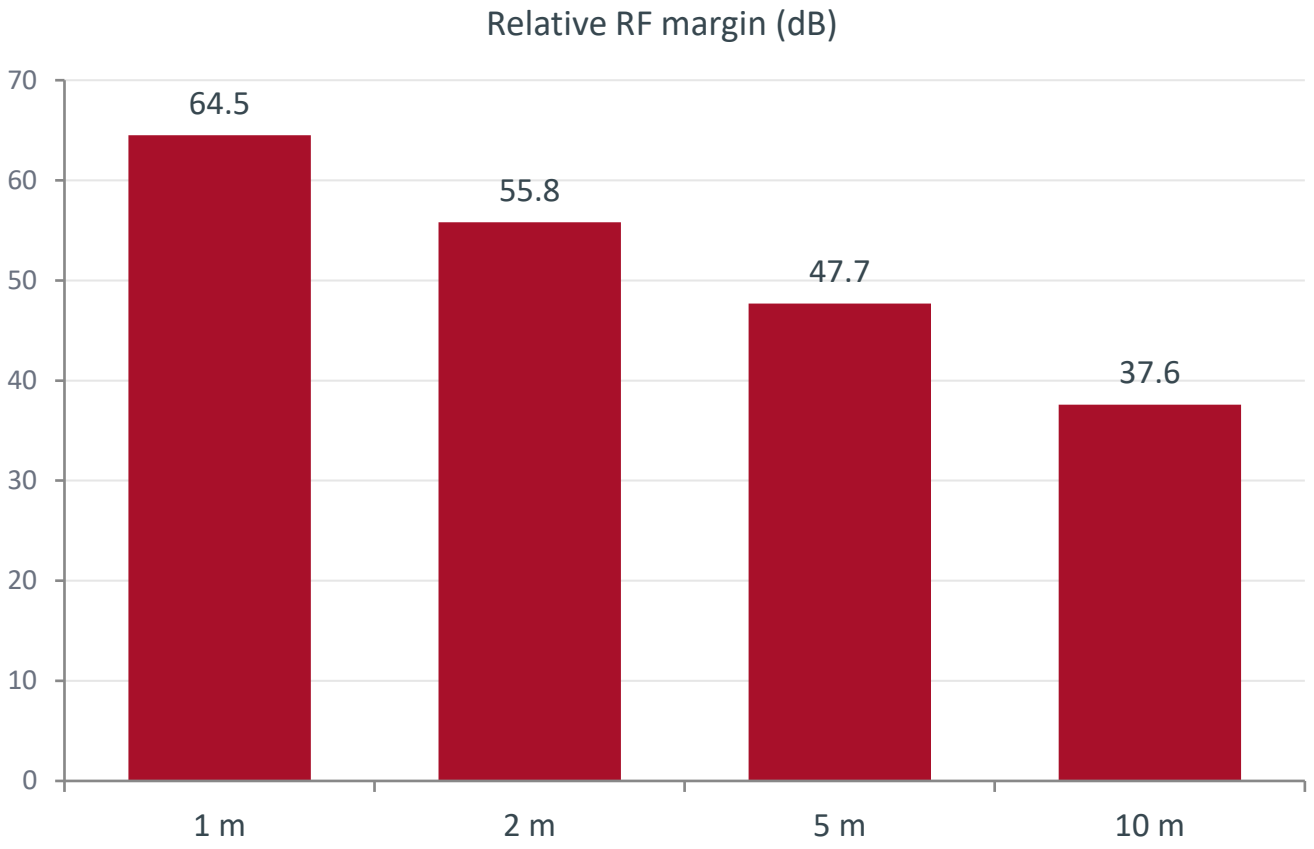
Access-code selectivity

Matched code against mismatched code, with the carrier still present.

Latency

Host timestamps either side of the USB serial round trip to the controller.

Range and signal margin



2.7

Path-loss exponent

26.9 dB lost over a tenfold increase in separation, against 20 dB for free space — consistent with indoor multipath.

Signal was never the binding constraint

Pre-emption succeeded at every separation tested, and 37.6 dB of margin remained at 10 m. The link had headroom left when the test campaign ended — which is what makes the outdoor range trial the natural next experiment.

Selectivity and response latency

0

Detections on a mismatched code

The carrier stayed visible on the spectrum display; nothing reached the controller.

≈36 ms

Receiver to controller

Mean of the USB serial round trip across all separations, SD 0.9 to 3.0 ms.

4 / 4

Separations pre-empted

1, 2, 5 and 10 m, each with the controller changing state as designed.

Where the time actually goes

36 ms	up to 3 s	≈ 0 s
Radio to controller	Safety yellow interval	Network and backhaul

The radio path is a rounding error against the yellow interval road safety requires anyway.

Known limitations, and the route past them

Payload carried no message content

Only the header reached the modulator, so detection worked while the message body did not.

Resolved: a Tagged Stream Mux ahead of the modulator.

Receiver halted on invalid packet lengths

The same header-only path produced intermittent halts, which set the ceiling on test separation.

Resolved with the payload path.

Close range sits in front-end compression

At 1 m the receiver compresses: 8.7 dB of drop where 6 dB is expected, with a raised noise floor.

Fix: lower receive gain, or pad at close range.

Buffer sizing, not beacon rate

A 50 ms interval suppresses underruns but drives duty cycle toward the regulatory threshold.

Fix: a buffer of 1,088 samples — exactly four packets.

Regulation and the link budget

The NCC short-range allocation

- Licence-exempt band: 433.05 to 434.79 MHz.
- 10 mW ERP below 10% duty cycle; 1 mW up to 100%.
- The prototype transmitted on 433.000 MHz, which placed roughly half the signal below the lower band edge.
- Moving the carrier to 433.92 MHz brings the occupied bandwidth inside the allocation.
- The 50 ms beacon interval used to mask buffer underruns also pushes duty cycle toward the 10% threshold.

Estimated margin at 300 m, at the 10 mW limit

Free space, n = 2.0	**+35 dB**
n = 3.0	**+11 dB**
n = 3.5	**–2 dB**

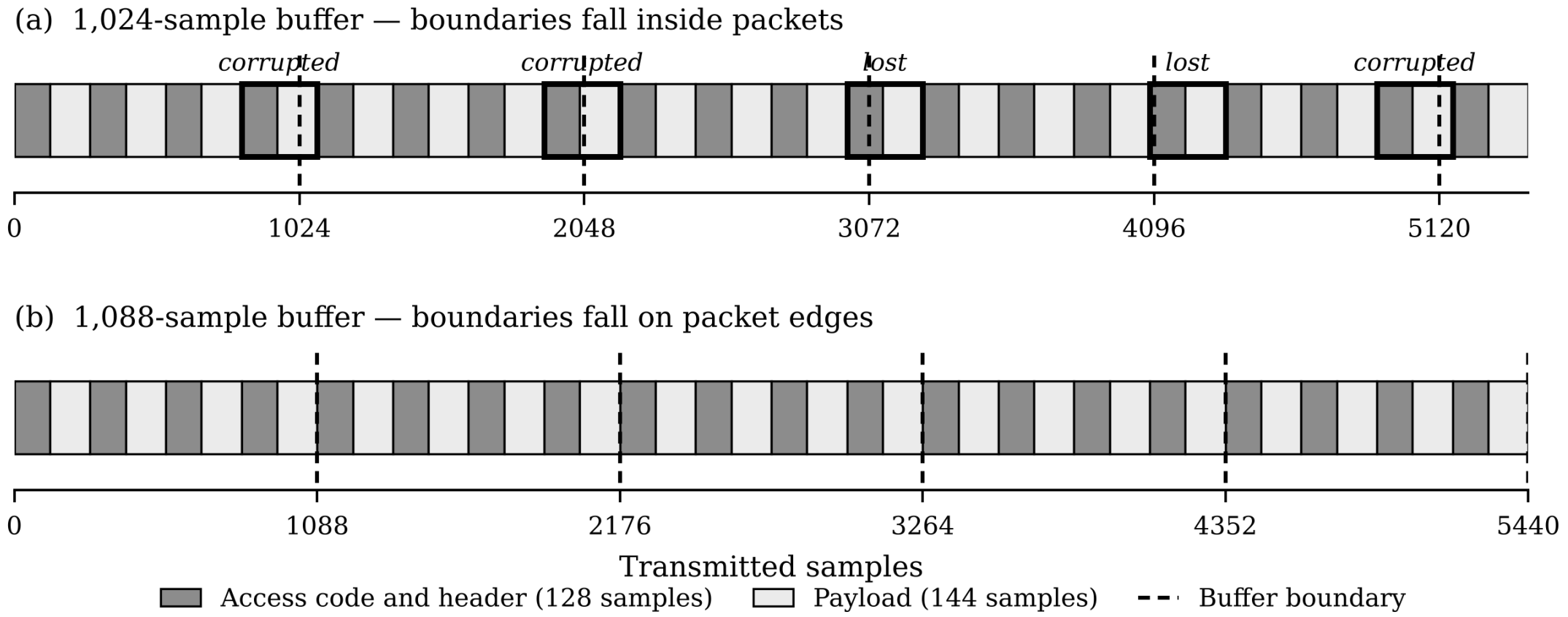
At the legal power limit a 300 m approach is comfortably within reach outdoors, and marginal only in heavy clutter. These figures set the design target for the outdoor campaign.

Measured values in full

Distance (m)	Peak (dB)	Floor (dB)	Margin (dB)	Pre-emption	Latency, mean ± SD (ms)
1	−25.5	−90.0	64.5	Yes	35.8 ± 2.5
2	−40.7	−96.5	55.8	Yes	37.2 ± 1.8
5	−48.8	−96.5	47.7	Yes	37.0 ± 0.9
10	−58.9	−96.5	37.6	Yes	35.8 ± 3.0

Peak and floor are relative display readings from the frequency sink at 40 dB fixed receive gain and FFT size 2048, not calibrated power. Margin is their arithmetic difference. Resolution bandwidth was not recorded. The number of trials at each separation was not recorded.

Why the buffer size mattered



A packet is 272 samples. A 1,024-sample buffer is not a whole number of packets, so boundaries fall inside packets — cutting the header loses the packet, cutting the payload corrupts it. A 1,088-sample buffer is exactly four packets.

Indicative cost

₦440,000

Per entire transmitter–receiver pair

₦430,000

The two SDR units

Roughly 88% of the total outlay.

₦20,000

Controller, signal heads, cabling

The Arduino Uno, LEDs and wiring that make up the rest.

Indicative approximate figures, not an itemised bill of materials. Conversions performed against dollar prices at the November 2026 official rate of ~₦1350 to the dollar.

Why SDR and not a fixed-function module

Everything that defines the protocol — waveform, access code, framing, correlation threshold — is set in software, so it can be changed without new hardware. That matters while the protocol and the regulations are still unsettled. Once they are fixed, the design can move onto a module, and this work is specifies what that module should do.

Conclusions and further work

What the work establishes

- The trigger chain works end to end, from beacon to signal head, at every separation tested.
- Access-code correlation gives real selectivity: a mismatched code produced no detections at all.
- Signal margin was ample throughout, leaving clear headroom for an outdoor campaign.

What comes next

- Repeated trials at each separation, reported with confidence intervals.
- Equal-duration selectivity runs with a logged packet count and a transmitter-off control.
- Outdoor range testing beyond 10 m, to verify the link budget by measurement.
- Payload recovery stabilised, and the carrier moved inside the licence-exempt band.

A pre-emption trigger that needs no network, no backhaul and no central control — demonstrated end to end, and ready for the road.

Thank you for listening .