SWER Broken Conductor Detection

Stage 2 – Final report

21 June 2022

Non-Disclosure Notice

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Acknowledgments

- The successful completion of this project took significant amounts of hard work, collaboration and flexibility across many companies.
- Moreover all this was made even more challenging with a global pandemic, lockdowns and world supply issues.
- We would like to thank the following people for making it successful despite the challenges:

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- We would also like to thank DELWP for their continued support for this project.

Executive summary

- This project focused on developing a cost-effective working prototype to demonstrate proof of concept in contributing to, or enhancing, the Victorian bushfire-risk mitigation activities of the PBSP.
- Fifteen transmitters and five receivers have been installed across five SWER networks in Victoria. These include the Springhill (near Kyneton), Mogil (near Tooborac), Quambatook (near Kerang), Kinglake, and Tarcombe (near Seymour) networks.
- Broken conductor tests were undertaken in June 2022 with isolation devices installed to emulate the effect of a conductor break in Springhill. The technology was 100% accurate in detecting loss of transmission across all these verification experiments.
- No false positives were experienced, however there were some close events, but only an issue for high sensitivity settings (set deliberately high for capturing critical network events)[1].
- The analysis of field data has revealed that accurate detection times from 0.4 seconds to 1 second are possible without false positives.
- The protection could be made slower or faster through remote configuration, with speed and sensitivity adjusted according to bushfire risk (i.e. higher sensitivity on TFB days).
- For the total network length of 175.54 km across five trial networks, the current solution cost per km can be projected as $2,600 per km.

1. Please see slide 26 for more details on false positives

Introduction

Background

Identified need

The need for a cost-effective bushfire mitigation solution applicable to SWER powerlines is widely recognised. On Black Saturday a break in the conductor on a SWER powerline in Kilmore East started a bushfire resulting in 119 fatalities as well as catastrophic damage to properties and the environment. Since then, technology such as REFCL's, SWER ACR's and cable undergrounding have occurred in response to Black Saturday. However more research is needed to mitigate the risks associated with SWER powerlines for the following reasons:

- Undergrounding and covered conductors are effective in mitigating bushfire risk however they are very expensive and are only feasible in the very highest bushfire risk areas.
- SWER protection is difficult. In two or three wire systems, substantial current flow to earth is abnormal and therefore wire down faults can be reliably detected. With SWER lines the current flow is through earth meaning this method cannot be used. As a result, SWER protection is far less sensitive and will not always detect faults that could cause fire starts.
- Early fault detection technology is showing promise at detecting issues associated with assets ahead of there being faults. However, this technology cannot provide real time isolation and therefore is not effective for conditions such as trees falling on powerlines.

Understanding this, a project was established to explore technologies that could possibly address this need.

Project objective

The overall objective of this project is to produce a cost-effective method to significantly reduce fire starts that are caused by SWER conductor breakage.

Project overview

Background

- Stage 2 of this project is a continuation of research initiated in 2018 by United Energy (UE) to develop a protection system that can rapidly (1 second) detect the break in an overhead powerline conductor before it hits the ground.
- This can be used to trip an ACR or other switching device to isolate the electricity supply to prevent bushfire and injury, operating like a REFCL for SWER powerlines.
- If successful, the SWER broken conductor fault detector will provide a low implementation cost relative to alternatives.
- Once developed it can be deployed quickly and provide significant risk reduction over a large area.

Project approach

- Overall the plan is to develop the technology in four stages as shown below:

	Stage 1	Stage 2	Stage 3	Stage 4
	Feasibility	Prototype	Commercialise	Deploy
Scope	Determine the feasibility of using PLC for SWER conductor breakage.	Create working prototype to demonstrate proof of concept.	Take prototype to a commercialised industrial product Carry out extensive testing before deployment	Manufacture and deploy products.

We are here

- Each stage of the project is designed as a gate to assess the effectiveness of the research before committing additional funding.
- Over the past 14 months, stage 2 of the overall project was successfully completed. This report covers stage 2.

Project goals

What did stage 2 set out to achieve?

At a high level, stage 2 of the project set out to achieve the following outcomes:

- Create working prototypes based on the research carried out in Stage 1.
- Install prototypes at 5 trial sites, representing varying degrees of communications difficulty.
- Evaluate prototype performance over a significant period of time.
- Measure and observe power line noise characteristics for the purposes of improving the prototypes.
- Create and trial improved 2nd generation prototypes.
- Measure prototype performance against success criteria.
- Determine if the technology is suitable to take to stage 3 (Commercialisation).

Measuring success

To determine if the prototypes will meet the project objective, four key success criteria were developed:

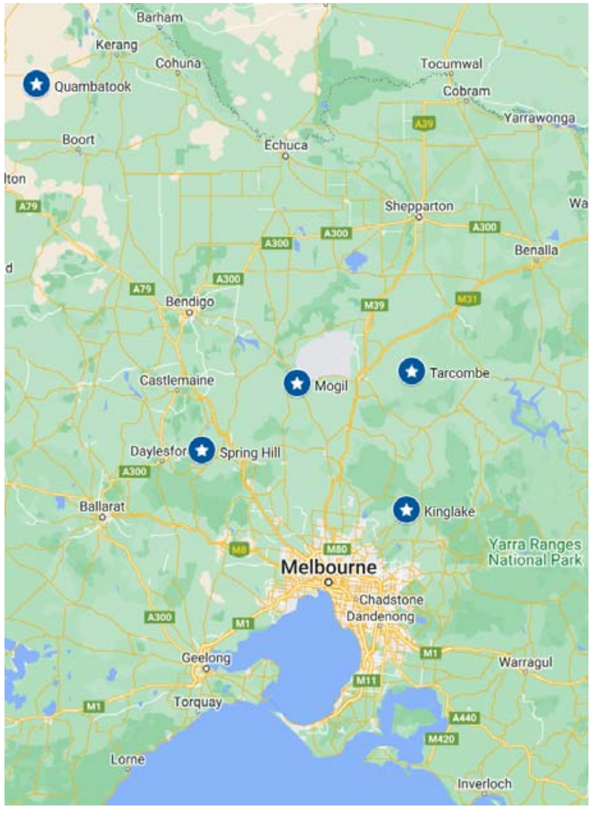
Description	Success criteria
Criterion 1 - Detection accuracy of conductor breakage	100% detection of conductor breakage
Criterion 2 - False detections (resulting in an outage)	< 1 false positive per year
Criterion 3 - Detection time	< 1 second
Criterion 4 - Solution cost (including installation)	<$10,000/km

All four success criteria have been tested as part of stage 2 and are discussed in detail in the coming sections.

Trial sites and results

Trial site overview

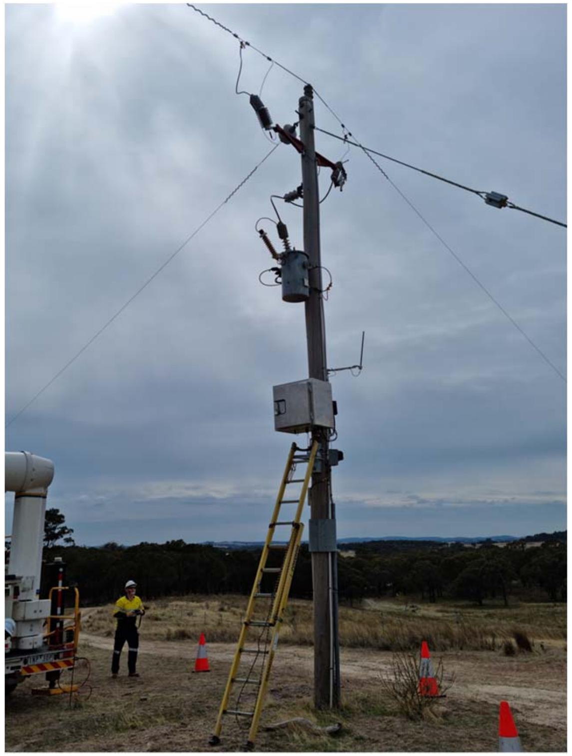
- This report provides a performance evaluation of the installed system of transmitters and receivers over five trial networks.
- Fifteen transmitters (TX) and five receivers (RX) have been installed across five SWER networks in Victoria.
- These include the Springhill (near Kyneton), Mogil (near Tooborac), Quambatook (near Kerang), Kinglake, and Tarcombe (near Seymour) SWER networks.
- The trials sites were chosen to provide a diverse range of challenges for the system, including:
  - **Near and far transmission** – Sites contained transmitters quite close to the receiver (e.g. 2.14 km in Springhill), and transmitters very far away from the receiver (e.g. 20.8 km in Quambatook).
  - **Large and small geographical area** - small SWER networks, such as Kinglake contained only 11.2 km total line length, where as Quambatook was a large SWER networks containing 84.65 km total line length.
  - **Mixed cable types** - The most challenging of all has been the Mogil SWER network due to its underground cable link.



Installed prototypes

- The following photos show the installed prototypes at Mogil and Quambatook.

Quambatook Transmitter 2 site – TX8



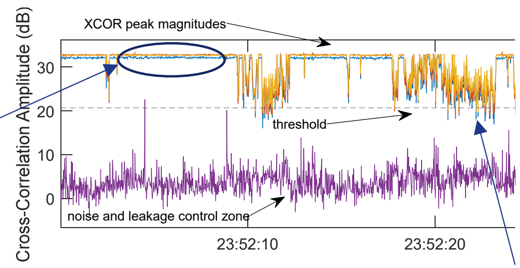
Mogil receiver site

Understanding trial site results

Signal cross correlation

- A Cross-Correlation (XCOR) plot shows the degree of similarity between the received and expected signals.
- The yellow, blue and red lines represent the 3 transmitters.
- A correlation threshold is set to decide if the correlation is strong enough to be called successful.
- The threshold is ideally set closer (lower) to the noise control zone (purple lines).

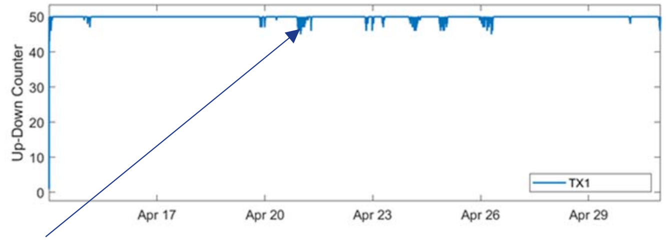
High correlation with expected signal



Noise causing lower correlation and therefore going under the threshold.

Reducing false positives

- To increase the resilience of the solution, a threshold Up Down Counter (UDC) was implemented.
- When the correlation is below the threshold, the counter is decremented.
- 50 successive under threshold counts (equating to 1 second of no communications) is considered a broken conductor.



When the correlation is below the threshold the counter is decremented

Springhill SWER network

- The first installation took place at the Springhill network in the Lauriston / Kyneton area, with a total line length of 15.31 km.
- 'Springhill 1 ISO' houses a 100-kVA rated isolation transformer and is the pole where the receiver is installed.
- The three transmitters were installed at the ‘Selle 1’, ‘Spring Hill P19’, and ‘May 6’ SWER substations as shown by the network schematic diagram.
- ‘May 6’ is the location of the furthest transmitter to the receiver, at around 7.5 km in distance from the ‘Springhill 1’ isolation substation.
- ‘Selle 1’ is the location of the closest transmitter to the receiver, at around 2.14 km in distance from the ‘Springhill 1’ isolation substation.

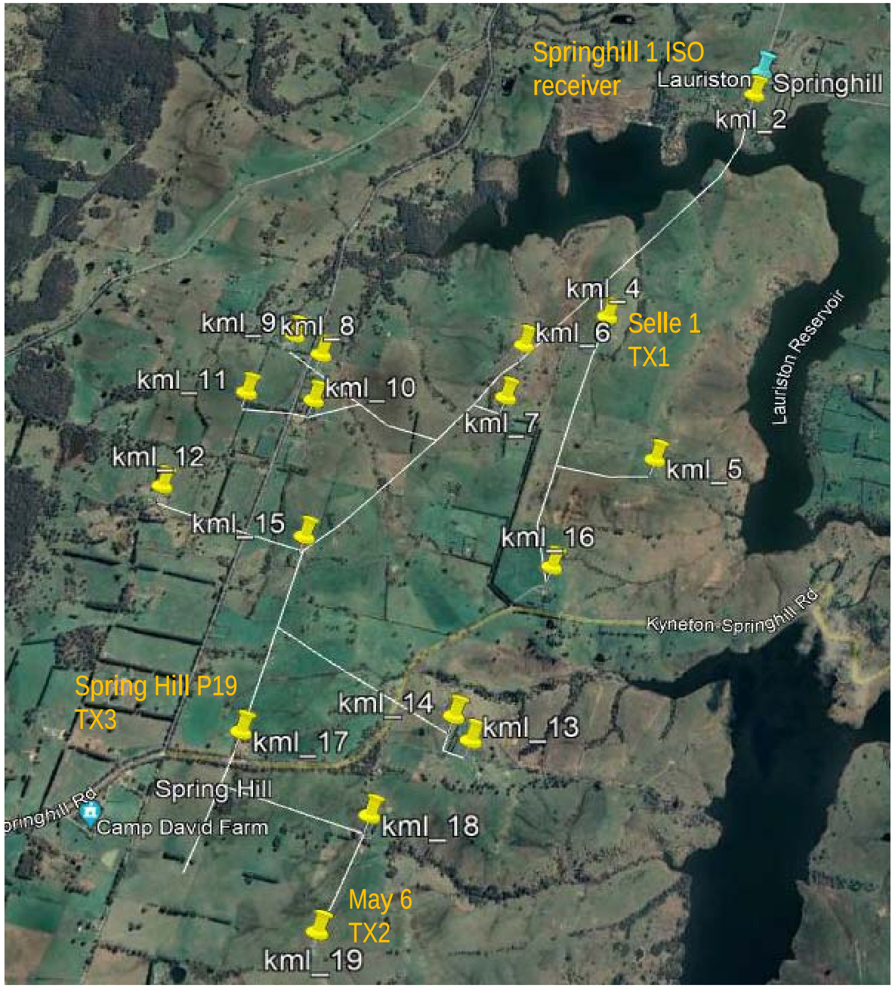


Figure 2: Springhill SWER network prototype install map

Springhill SWER network

- Figure 3 shows the Springhill XCOR peak amplitude plot and UDC statuses from 14/04/22 to 01/05/22.
- No false positives (i.e UDC = 0) despite volatile network noise (purple line; often as high as the transmitters).
- Noise bursts look extreme, however no false positives were observed.
- These results were achieved through operating transmitters at around 10% of full power capacity.

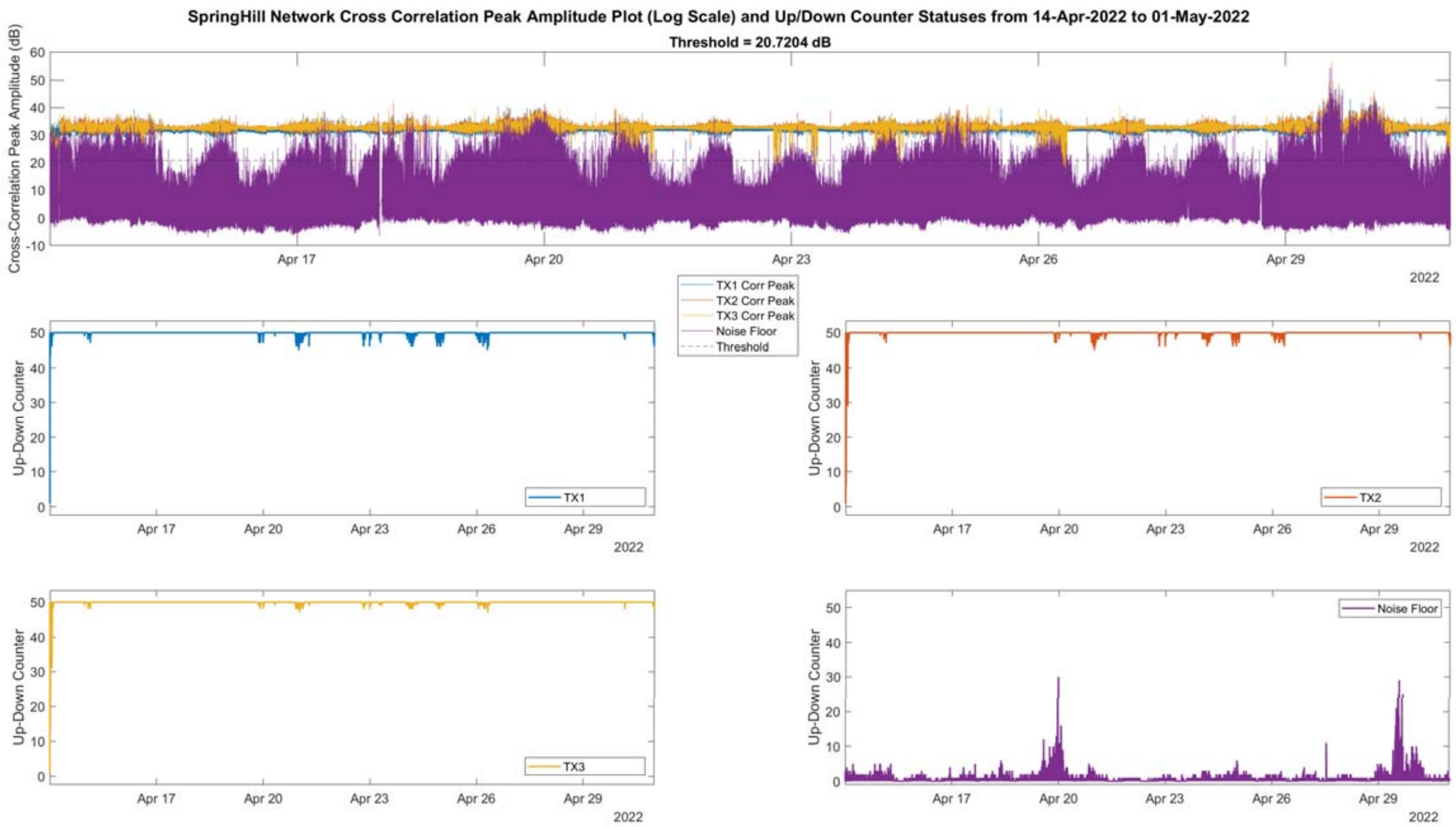


Figure 3: Springhill SWER network field application results.

Mogil SWER Network

- The Mogil SWER network is located near the town of Tooborac and has a total line length of 37.38 km.
- The was receiver installed centrally within the network at the MOGIL P28 substation.
- This was undertaken in an effort for balancing the transmitter distances away from the receiver such that extremely long transmitter to receiver paths could be avoided in any direction.
- The three transmitters were installed at the 'Taylors RD P9E', 'Mogil South P4', and 'Mogil P2' SWER substations. 'Taylors RD P9E' is the furthest transmitter to the receiver, approximately 9.82 km from the receiver (at Mogil P28).

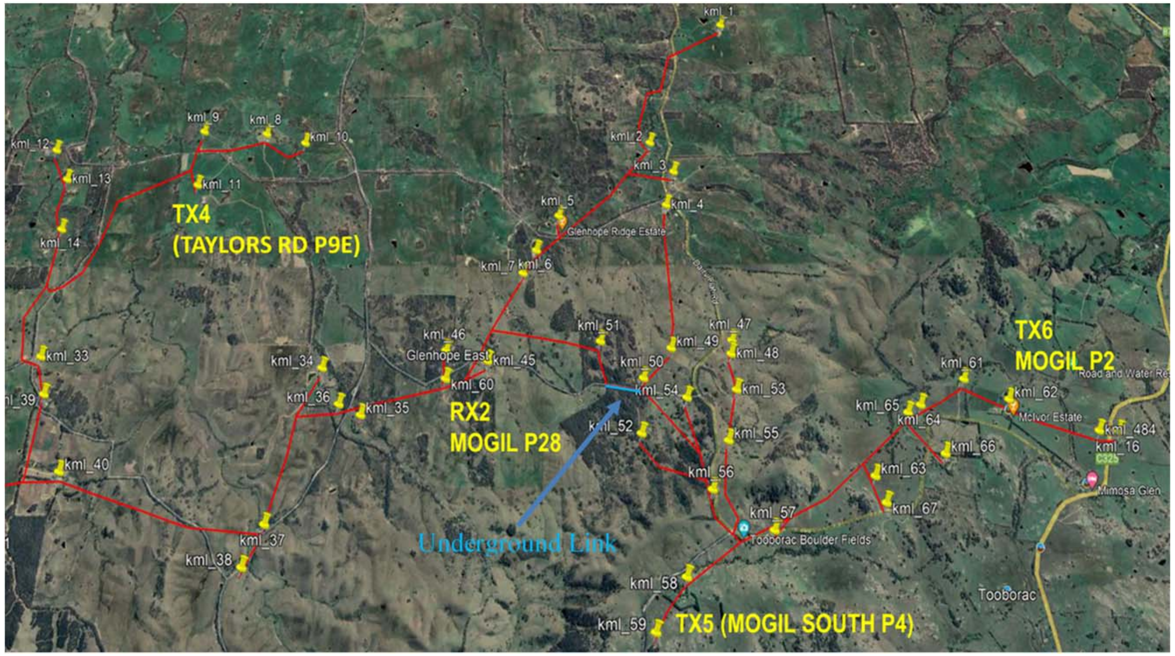


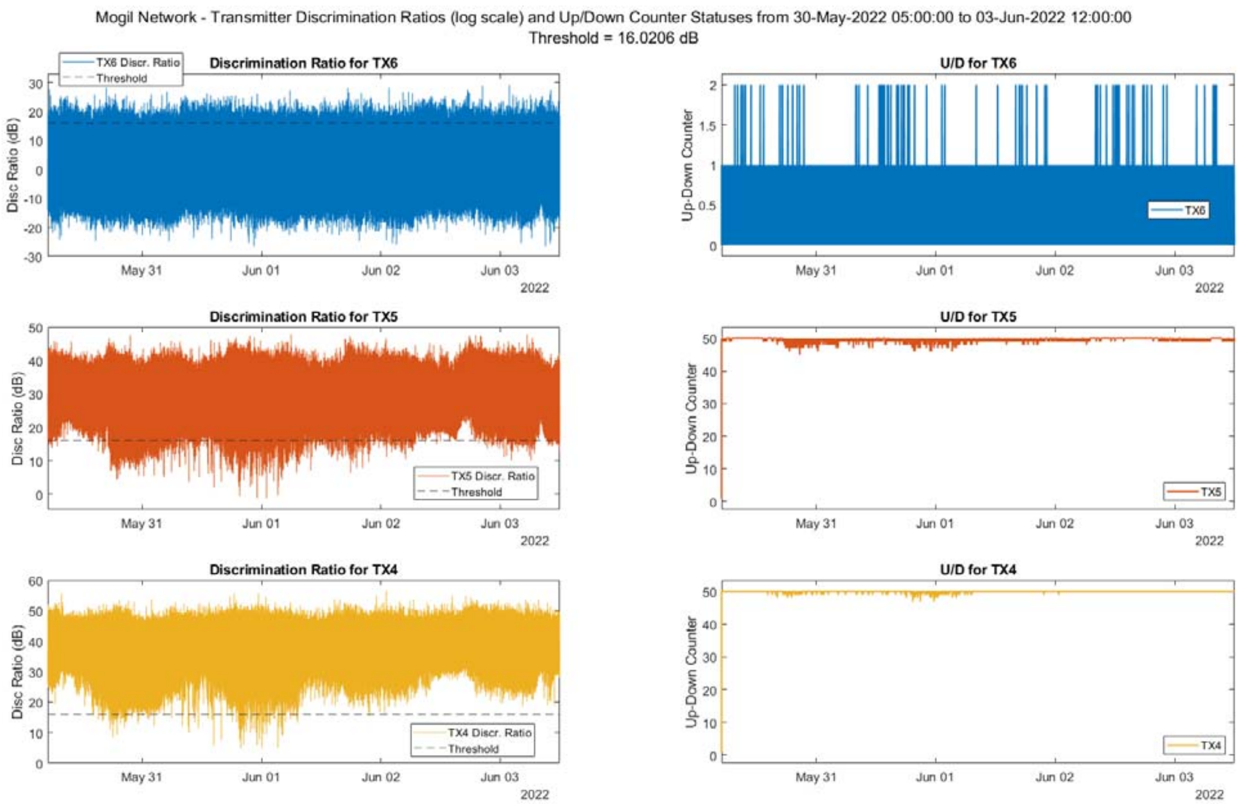
Figure 4: Mogil SWER network transmitter and receiver installation map.

- One key characteristic of the Mogil network is the 35-mm cross-sectioned Aluminium underground link.
- Underground links generally have higher capacitance, which imposes a challenge for the transmission of High Frequency (HF) signal components over the link.

Mogil SWER Network

- The higher capacitance of the underground cable caused attenuation of the HF signals.
- To address this challenge, a new modulation scheme was deployed on Mogil.
- Transmitting 10 kHz bandwidth signals at low frequencies (e.g. 30 kHz to 40 kHz).
- Figure 5 shows the discrimination ratios and UDCs analysed from 30/05/22 to 03/06/22.
- The new scheme was successful in discriminating transmitter 4 (TX4) and transmitter 5 (TX5), but transmitter 6 (TX6) proved more challenging due to its extra 2 km distance from the link.
- In networks with underground links: careful selection of transmitter sites with close proximity to the link, repeaters before/after the link, ACR placement each side of the link, or single-core underground cabling may be required.

Figure 5: Mogil SWER network field application results.



Quambatook SWER Network

- The Quambatook SWER network is located near the town of Kerang and has a total line length of 84.65 km.
- Unique feature of this network is it contains an Aluminium Galvanised Steel Reinforced conductor on the main spur.
- Aluminium conductors have lower resistivity, resulting in better transmission.
- The receiver was installed at kml_23 which is approximately 1.67 km from the ACR pole.
- Three transmitters were installed at the ‘SandHills 45’, ‘Ralph 8’, and ‘Denyer 17’ substations.
- Transmitter 7 (TX7) is ~ 20.8 km from receiver making it the longest communication channel in the entire project.

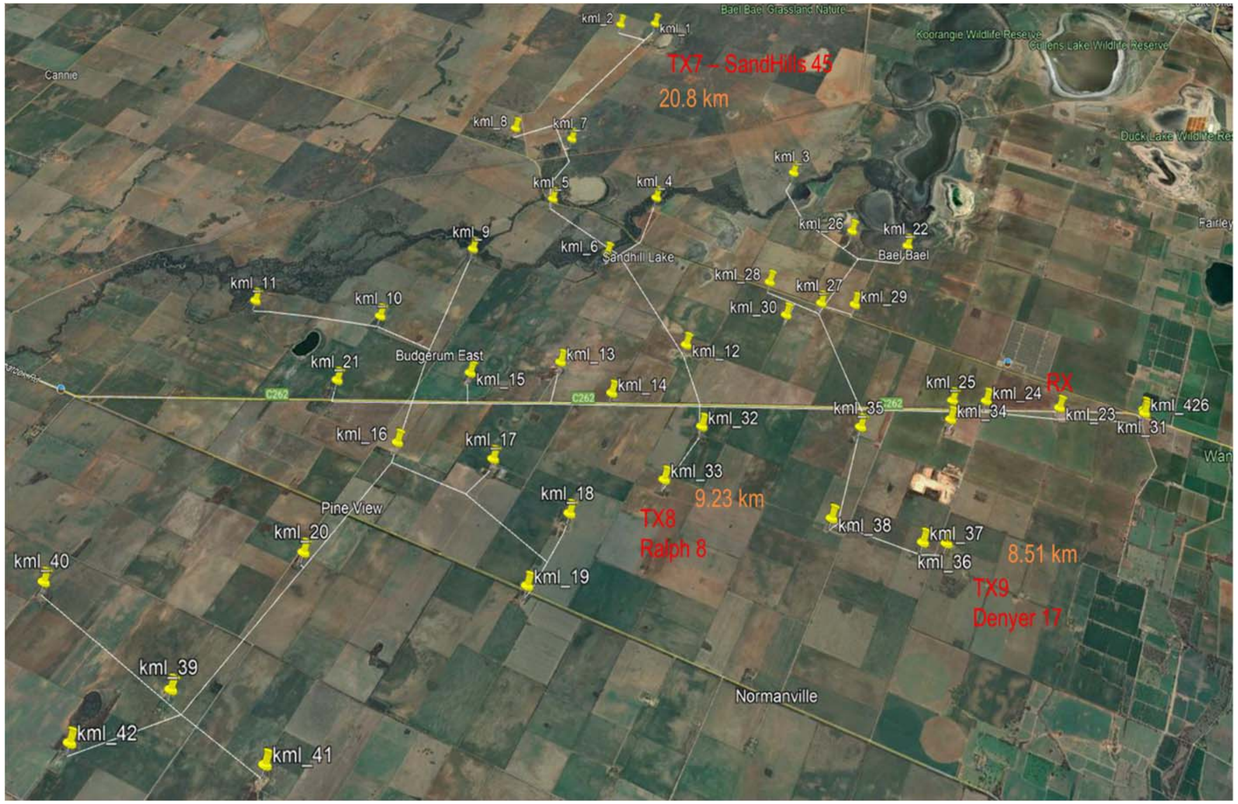


Figure 6: Quambatook network map showing prototype installations.

Quambatook SWER Network

- Figure 7 shows XCOR amplitude plot and UDCs for the three transmitters from 31/05/22 to 03/06/22.
- Despite tightly set thresholds, the UDCs points to very reliable transmission.
- Good outcome considering the very long communication channel (TX7,~20.8 km).
- The threshold deliberately set high to capture network activities. After commercialisation, threshold likely to be set lower.

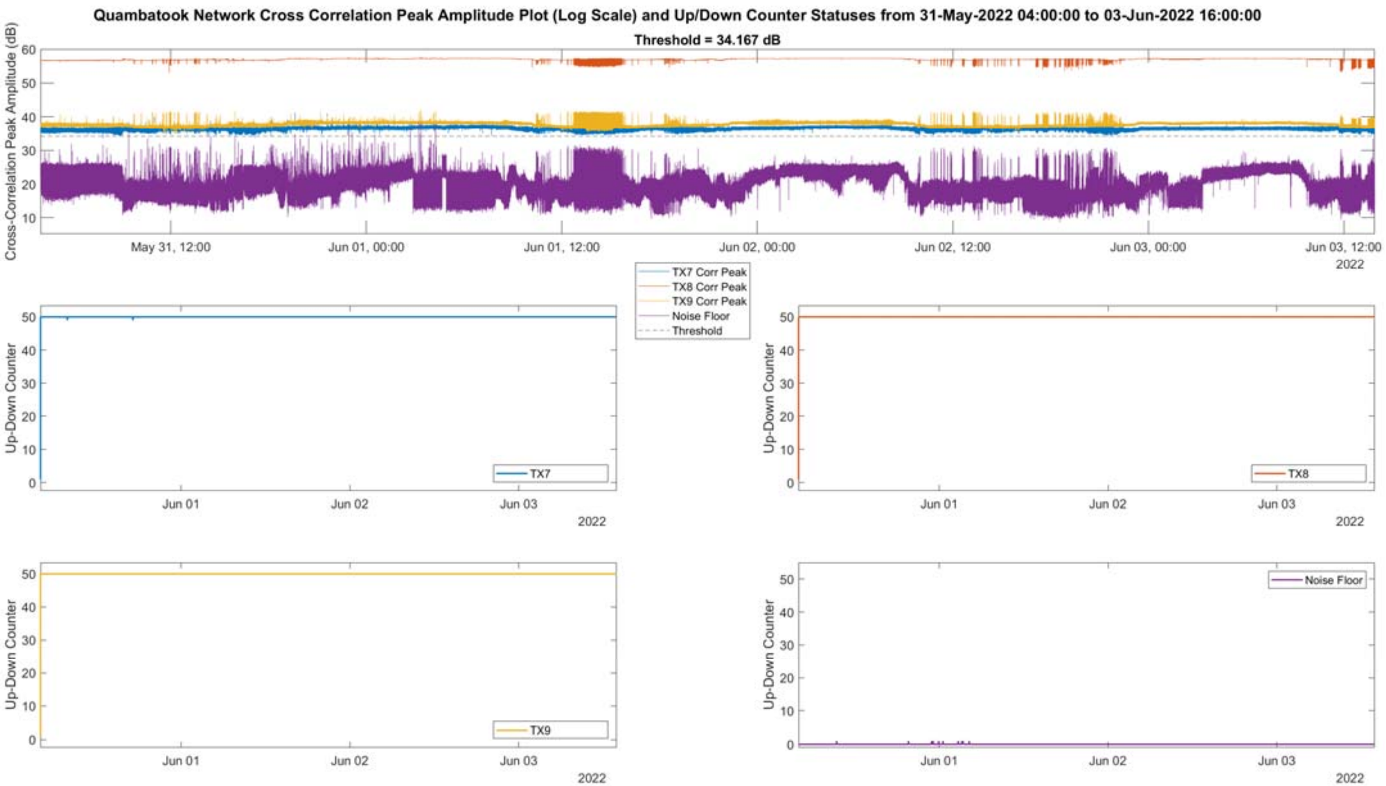


Figure 7: Quambatook SWER network field application results.

Kinglake SWER Network

- Kinglake was the fourth installed network. One of the areas most destructed by the Black Saturday bushfires of the 7th February 2009. Installation of the prototypes on this network was therefore historically notable.
- The Kinglake network is the smallest trial network with a total line length of 11.2 km, however it represents the highest density network.
- Transmitter 11 is the most distant transmitter, which is approximately 4.4 km from receiver and contains a split-phase SWER substation.

Figure 8: Kinglake SWER network installation map.

Kinglake SWER Network

- Figure 9 shows the UDC statuses from 3/06 to 10/06.
- A threshold level of 49.18 dB was sufficient in maintaining stability except for a brief period on the 7/06/22 when UDC_{TX11} = 45.
- UDC_{TX11} recovers after this brief interruption.
- No false detections present.
- TX11 is weaker than the other two transmitters due to it being the most distant transmitter and containing a split-phase transformer.

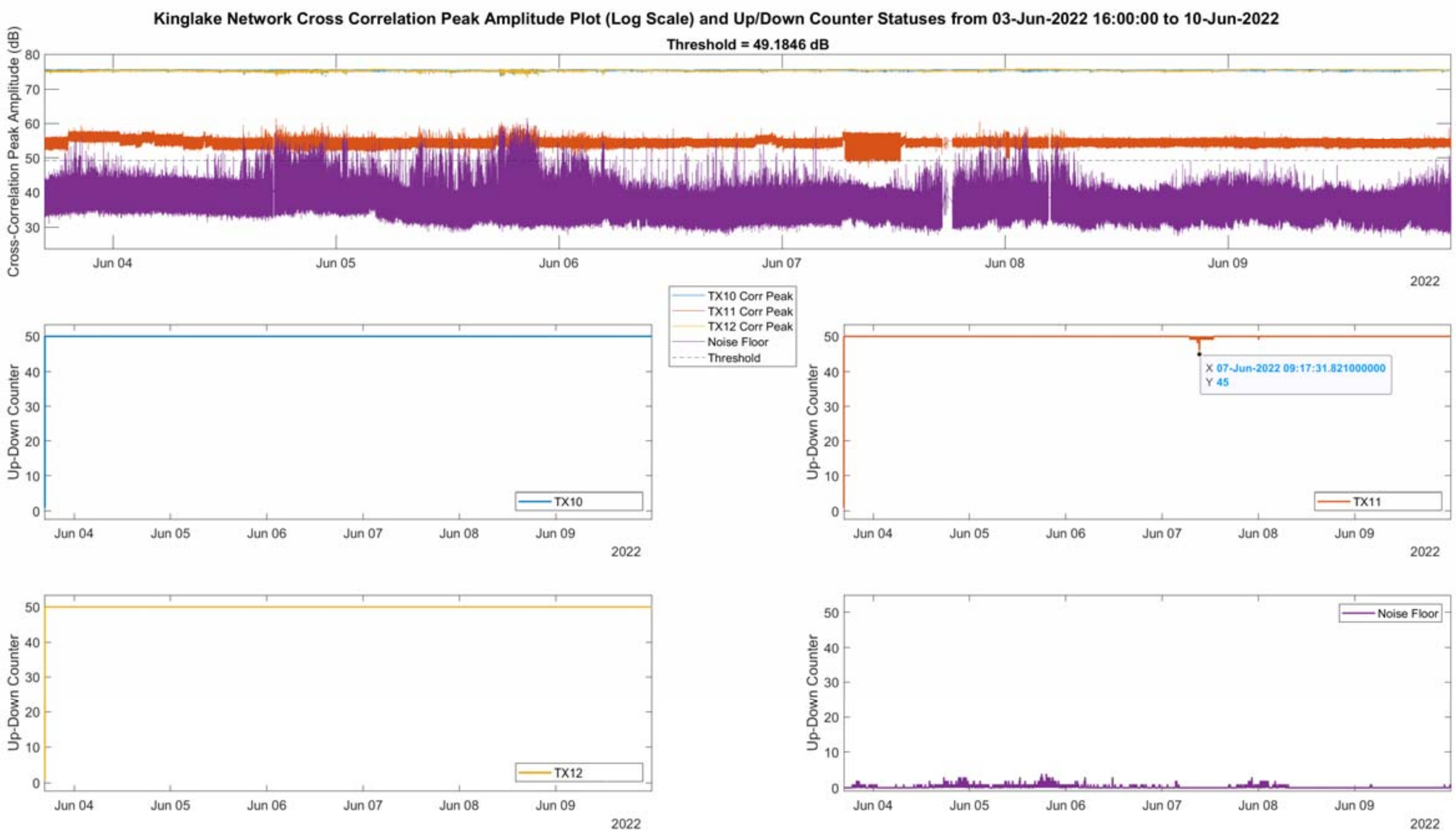


Figure 9: Kinglake SWER network field application results.

Tarcombe SWER Network

- Fifth network installed near Seymour. Relatively long but has few interconnecting spurs. The receiver was installed on the ISO pole due to space availability. This network has 3-strand SC/GZ type conductors.
- The three transmitters were installed on the poles with the Business IDs of 3909474 (TX13), 3902816 (TX14), and 3902815 (transmitter15). TX15 is the distant transmitter, which is approximately 19.48 km from receiver.
- TX14 has a split-phased configured transformer (2 × 240 V supplies, 180° out of phase) with a single LV filter connected on each phase to stop HF signals from penetrating into customer's supply.

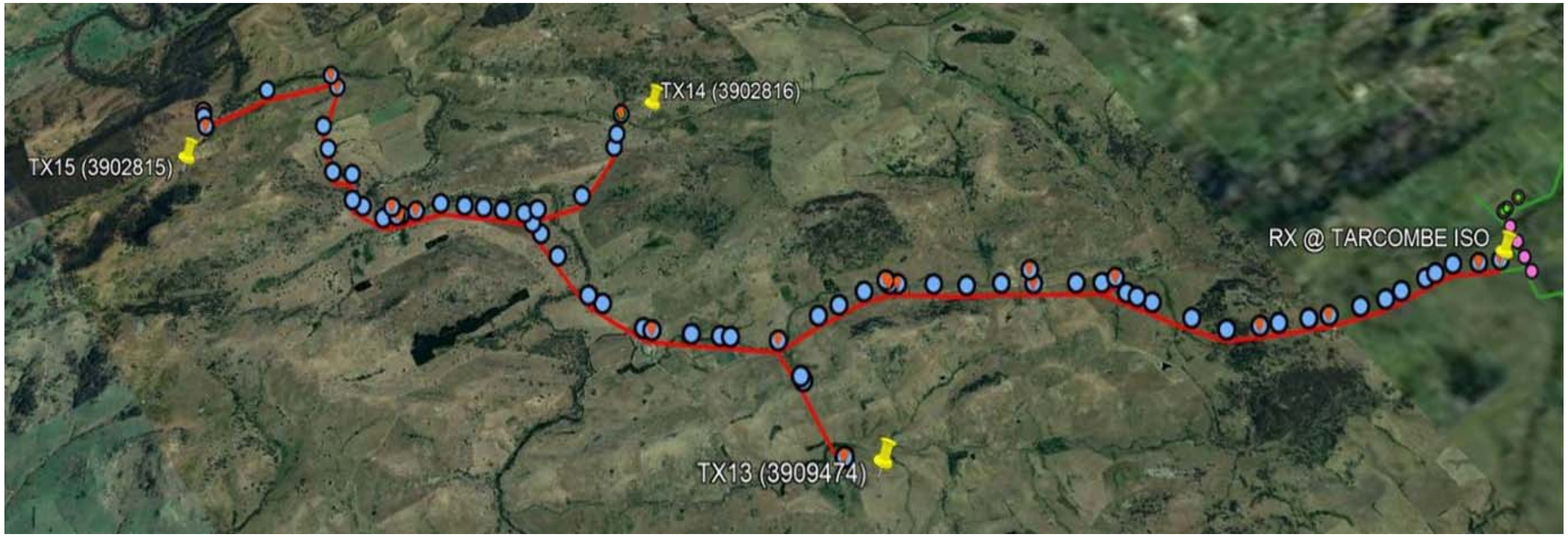


Figure 10: Tarcombe SWER network map showing install locations.

Tarcombe SWER Network

- Figure 11 shows XCOR/UDC statuses for the network on 16/06/22.
- Data covers TX14 and TX15.
- TX13 was off during this data capture and subsequently switched on.
- Both transmitters can be received without any down count challenges.
- Reception of transmitter 14 was improved with an LV-filter per phase despite the split-phase SWER transformer being connected at this location.

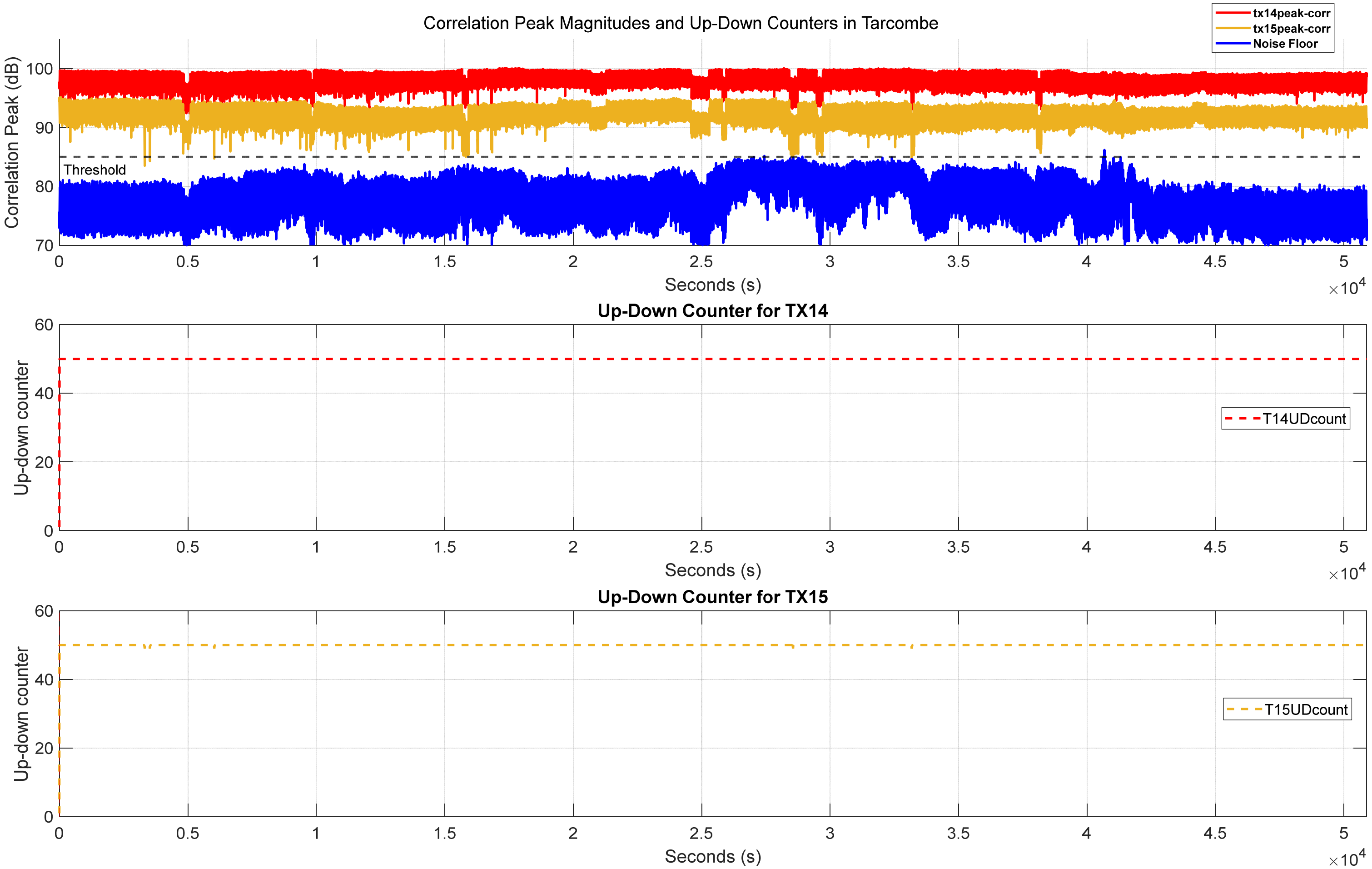


Figure 11: Tarcombe SWER network field application results.

Performance

Performance against success criteria

The following table summarises the performance against the success criteria.

Description	Success criteria	Performance summary
Criterion 1 - Detection accuracy of conductor breakage	100% detection of conductor breakage	100 % accuracy rate was achieved in detecting loss of transmission from technical problems, simulated events on trial networks, and experiments on test rigs on the Springhill SWER network.
Criterion 2 - False detections (resulting in an outage)	< 1 false positive per year	No false positives experienced. Few close events, but only present due to the highly sensitive threshold adopted[1].
Criterion 3 - Detection time	< 1 second	Data revealed that accurate detections with no false positives from 20 power cycles (0.4 s) to 1 second are possible. Minimum advisable system detection time of 0.4 s followed by circuit breaker and Automatic Circuit Recloser (ACR) trip delays.
Criterion 4 - Solution cost (including installation)	<$10,000/km	The total solution cost is $2,600 per km including hardware and installation costs.

1. Please see slide 26 for more details on false positives

Criterion 1 - Detection accuracy of conductor breakage

- In June 2022, two critical tests were undertaken on the Springhill network for simulating the broken conductor events using isolation devices.
- Field tests were undertaken to build further confidence in the technology.
- One key concern was that conductor breakage might not be reliably detected as Radio-Frequency (RF) transmission may result in signal being fully or partially received even though the conductor is broken.
- Another key concern was the potential for transmission leakage through earth return, when a conductor breaks.
- Isolation devices (Bluetooth MSI's) were installed at the Maylands 4 and Springhill 9 poles in the Springhill network.
- A conductor breakage was simulated through engaging these isolators, when the continuity of the line was broken.
- The tests also included earthing of the conductors.

Figure 12: Installation of the MSI for simulating a broken conductor in Springhill.

Criterion 1 - Detection accuracy of conductor breakage

- Figure 13 shows the results from Test 2 where the conductor was isolated between the 2 × transmitters and the receiver.
- Transmitter 2 and 3 XCOR plots decline to the noise floor and counter values decay linearly.
- Counters for both transmitter 2 and 3 reach zero in approximately 1 second, correctly indicating a conductor breakage.

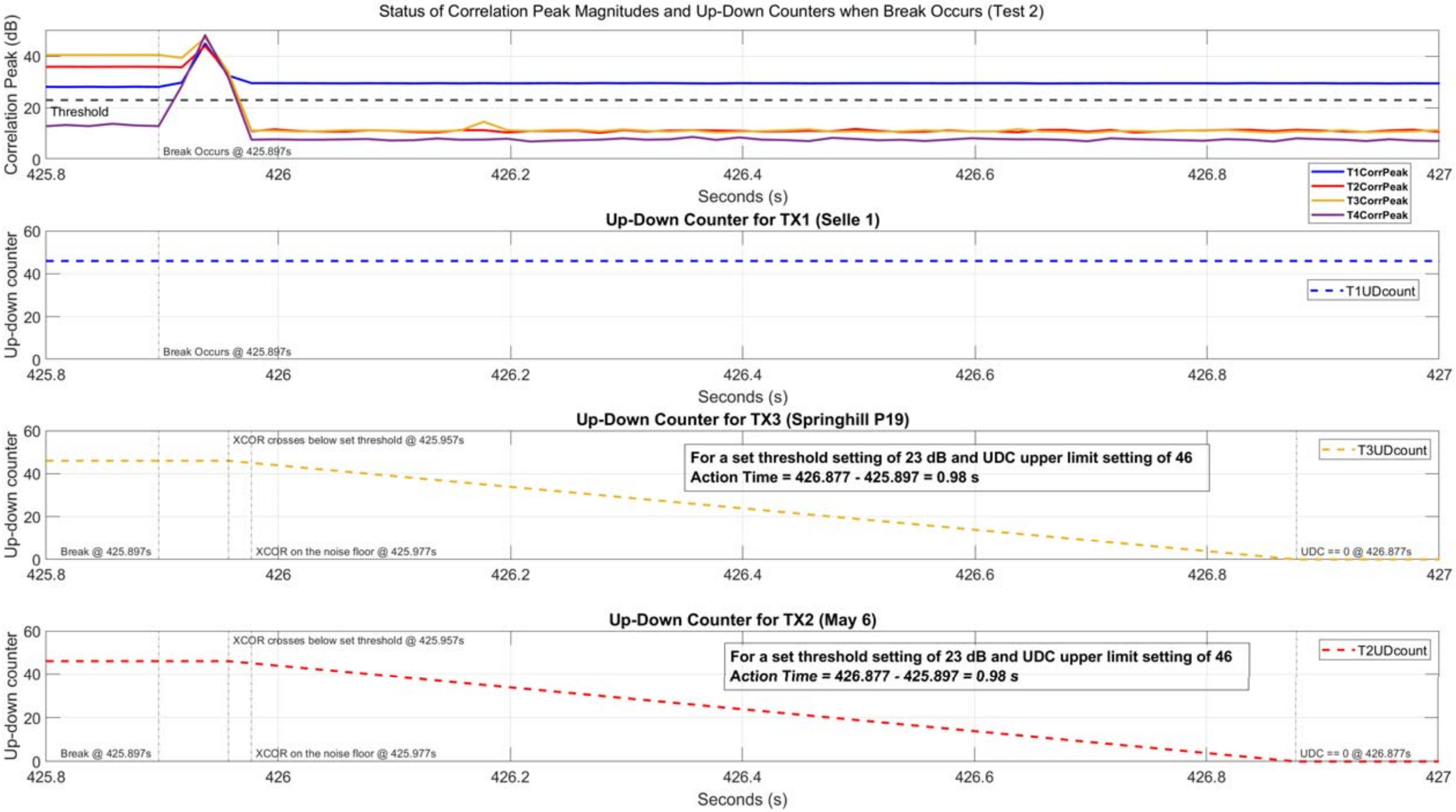


Figure 13: UDC statuses during a broken conductor simulation test in the field.

Criterion 2 - False detections (Resilience to noise)

- Resilience to noise is achieved using a simple counter approach that requires a one second interruption in transmission for the counter to reach 0.
- Progression of the XCOR peak and UDC is illustrated in Figure 14 during the period from 8/01/22 to 15/01/22.
- The network noise occasionally reaches a high level, often as high as some of the transmitter signals.
- The high noise coincides with poor weather events with the Melbourne Airport weather data indicating thunderstorms on Jan 13 to 14.
- Our hypothesis is that poor weather → high noise.
- Although the noise looks extreme in the plots, these noise bursts last only for a short time and never long enough to cause a false trigger.
- Overall, no false positives were experienced with the enhanced system. This included pulse per second functionality, power equalisation, application of windowing and synchronised clocks.
- A few close events occurred for highly sensitive thresholds (deliberately set for testing purposes). Lower thresholds could avoid close events.

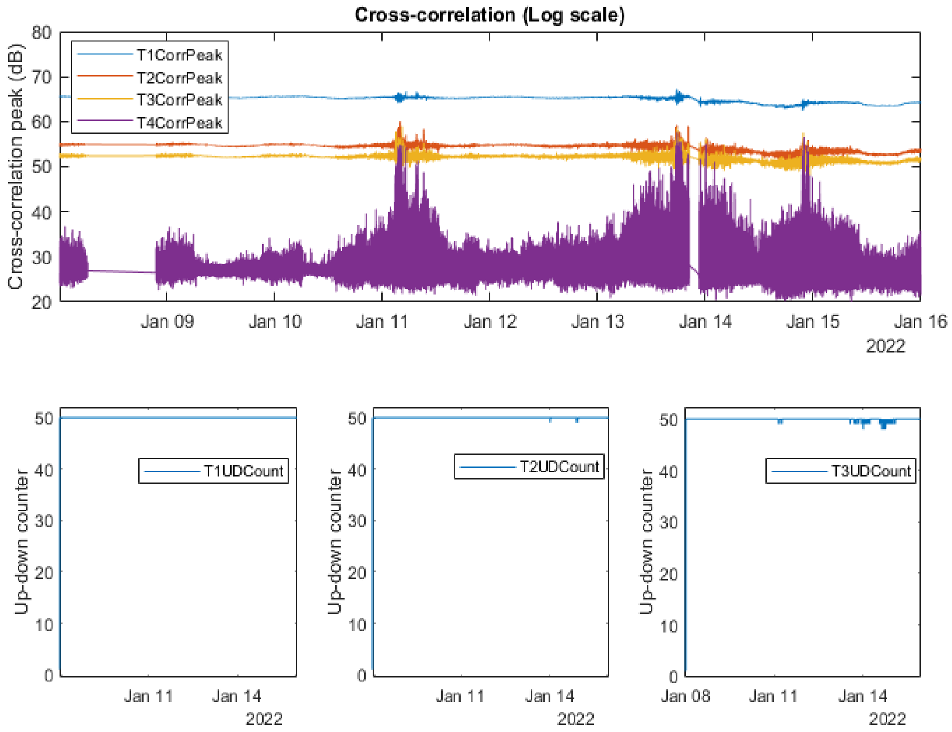


Figure 14: The link between network noise and weather

Criterion 3 – Detection Time

- The detection time setting is flexible and can be set and trivially adjusted as discrete increments of one decision block (20 ms).
- The protection could be made fast by tripping as soon as one negative decision block occurs (in just 20 ms). Nevertheless, that would be undesirable and would not provide any balance between reliability of supply and protection speed depending upon the risk on any particular day or season.
- The default counter (UDC) setting is 50, resulting in a one second trip time.
- The research team believes that an UDC setting of 20 might be the minimum advisable, which equates to a system detection time of 0.4 s (20 × 20 ms).
- In stage 3 of the project any delays in tripping a circuit breaker or Automatic Circuit Recloser (ACR) must be taken into account.
- Settings for extreme (code red), moderate, and low fire risk hierarchy could be adopted, where the UDC limits could be adjusted based on seasonal or even daily requirements.
- Currently, there is full remote access to the transmitters and the receiver to enable such online modifications with ease.

Criterion 4 – Solution cost

- The calculated approximate hardware and data costs for the installation of three transmitters and one receiver on a SWER network is around $30,100.
- The total segment length of the five networks is approximately 175.54 km.
- The prototype hardware and running cost total is therefore $857.35 per km.
- The cost for AusNet Services and Powercor labour and materials add up to $1,742 per km.
- The total solution cost is then ~ $2,600 per km, which is far less than the $10,000 per km budget criteria.
- A commercialised product is likely to be significantly lower than this figure, as component costs can be optimised after the prototyping phase.

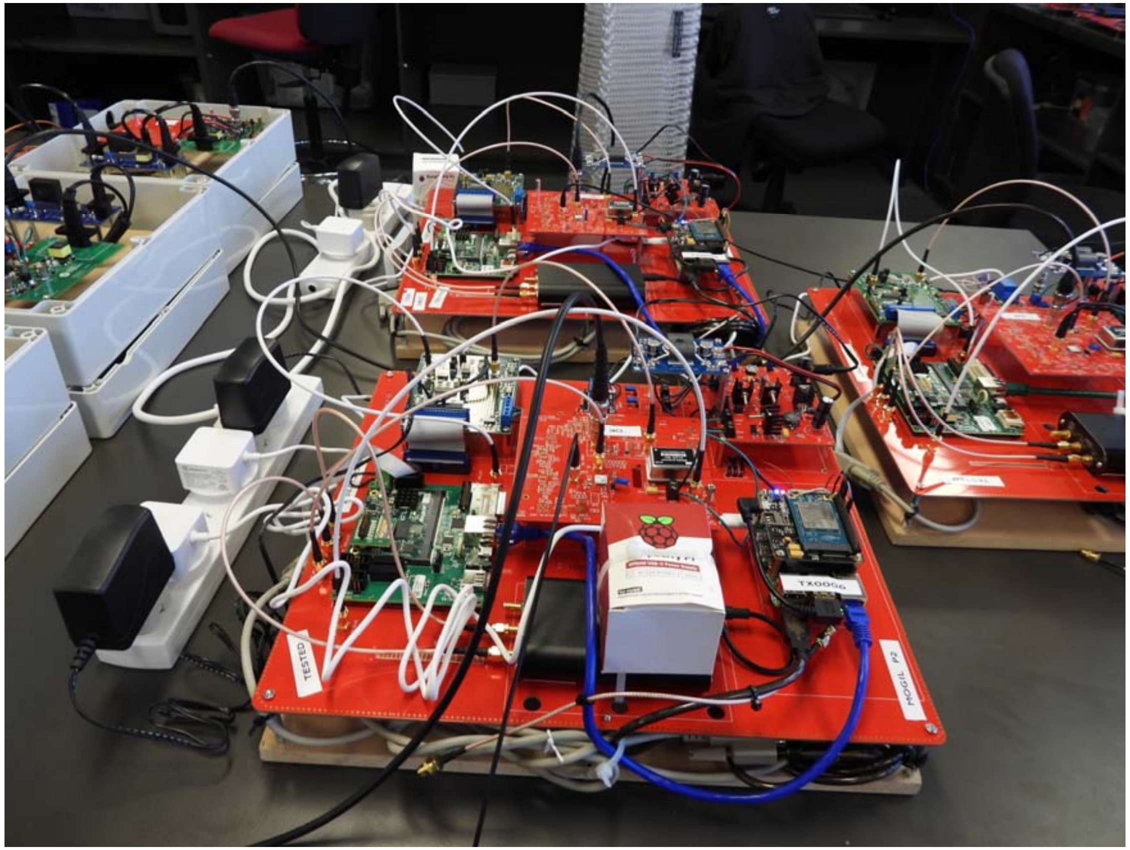


Figure 15: Three transmitters during a lab test

Conclusions

Conclusions

- Stage 2 of this project successfully demonstrated that the developed prototypes were able to meet the key success criteria for the 5 trial sites.
- The overall scheme relies on nonstop transmission of tests signals from various transmitters placed on network ends and listening to these test signals at a receiver placed preferably at the beginning of the network. If the signal is lost, then the ACR will be tripped cutting the down-stream power supply.
- This report outlines the performance of the installed system of transmitters and receivers in five trial networks including Springhill (near Kyneton), Mogil (near Tooborac), Quambatook (near Kerang), Kinglake, and Tarcombe (near Seymour).
- Successful transmission was possible in all trial networks. The most challenging trial network has been the Mogil SWER network with its underground cable link.
- Our experiences show that in networks with underground links (on the critical path), careful selection of transmitter sites will be paramount. The use of repeaters before/after the link, an ACR on each side of the link, may be required.
- Split-phase SWER transformers also require special attention. These were encountered in the Kinglake and Tarcombe networks. While selection of split-phase connected SWER substations can easily be avoided (i.e. plenty of transmitter options in most networks), if transmission from such a double-phased SWER transformer becomes necessary, then installation of LV filters on each phase should be considered.

Recommendations / Next steps

The following recommendations have been made to ensure the continued success of the project.

Recommendation 1

Continue to observe installed trial sites over the 2022/23 summer period

- Many of the trial sites were installed towards the end of the project.
- Before proceeding to the next stage it would be beneficial to observe the performance of all of the trial sites, especially to ensure that false positives are not detected over a summer period.
- Collection of more data will also aid in the case that performance needs to be improved.
- Additional time may also provide information on performance in real fault scenarios.

Recommendation 2

Carry out initial research into device integration

- To date the prototypes have been operating in isolation, not controlling any switching devices to cut out the electricity.
- Whilst the trial sites continue, it is recommended that research be done in how to integrate the broken conductor detection system with currently deployed switching devices (such as SWER ACRs) and SCADA systems.

Recommendation 3

Fund the project to complete Stage 3

- Secure funding to continue the project into commercialisation (Stage 3).
- This would be scheduled to start in Q2 2023.