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ENVIRONMENTAL DATA COLLECTION AND SIMILAR RADIO LINKS TO PROVIDE ONE-WAY MESSAGE TRANSFER :

HOW TO COVER A MAXIMUM AREA WITH BATTERY-POWERED TRANSMITTERS ?

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ENVIRONMENTAL DATA COLLECTION AND SIMILAR RADIO LINKS TO PROVIDE ONE-WAY MESSAGE TRANSFER : HOW TO COVER A MAXIMUM AREA WITH BATTERY-POWERED TRANSMITTERS ?

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ABSTRACT

Based on compact and battery-powered remote sensors, a wide-range data collection network has been set up. In its first implementation, environmental radioactivity is measured and transmitted in an hourly cycle via a UHF radio link. In order to provide several years of maintenance-free operation in the open air, the design effort has been directed towards ultimate stability and minimum battery consumption on the transmitter side. By employing state-of-the-art receiver technology at the base station, a radio horizon of more than 100 km (line-of-sight) can be covered with such an application-specific radio sensor network.

While demonstrated with environmental monitoring, this novel approach is attractive for all kinds of low-rate data links, especially for multiple simplex connections from remote locations. Installing an application specific radio network can be an attractive alternative compared to the prolonged use of public cellular services. Arguments may arise from insufficient field-strength (far away from urban areas), from aspects of accumulated cost, from maintenance interval, or simply, when link-availability in case of a severe emergency is an important aspect.

INTRODUCTION

There are several parameters related to chemistry, physics, oceanography, geo-sciences and meteorology which can be monitored continuously without major technical problems. Some of these are associated with a high degree of public concern. In several countries, this has led to the installation of sophisticated early-warning networks to protect the population against potential hazards: avalanches, forest fires, volcanic eruptions, earthquakes, airborne radioactivity - to mention just a few.

Today, there is only one problem remaining: Most of these sites, where the measurements have to be taken, are far away from civilisation, and consequently, there is no mains power supply available, nor a telephone cable for on-line modem connection. Frequently, in these sparsely populated regions - where the early-warning sensors should be placed to ensure optimum performance - there is no access to wireless communication services like GSM, TETRA, DECT, DCS-1800 or US-CDMA.

FIG. 1: *Focused on the personal communication market in urban areas, public cellular networks are not an appropriate vehicle for environmental data collection.*

In principal, these obstacles can be overcome. Historically by digging miles and miles of cable. More recently by employing conventional (and power-hungry) radio-modems with a few watts of RF-output or VSAT terminals (incl. their bulky antennas). But unfortunately, in these “wireless” approaches still quite a lot of wiring has to be installed on-site. Weather-tight enclosures, a pylon construction (for antenna and solar panel), protective fences etc. add up quite a lot of extra-cost to the project budget.

FIG. 2: A *new generation of compact outdoor stations for remote gamma monitoring at Mumbay/India. The system, hardly visible in the upper right (next to the trunk), is measuring airborne radioactivity and transmitting data via UHF radio-link every hour.*

Consequently, the majority of today’s network budgets is *NOT* spent for the primary intention - for the “sensor” - *BUT* for manpower to install, protect and maintain telecommunication gear in the open sky.

Finally, considering the net baudrate in the above mentioned telemetric systems (typically a few bytes per hour), conventional off-the-shelf radio modems (handling dozens of kiloBaud) look a little bit like “overkill”.

A ROBUST TERRESTRICAL RADIO NETWORK SPECIALISED IN LOW-RATE DATA COLLECTION

The author is looking back on more than ten years of experience in the implementation of systems for the measurement of environmental radioactivity (cable-bound as well as autonomous data logging). In this field it is important to guarantee for non-stop operation of environmental data collection networks over years. Recently, a new generation of compact gamma monitoring stations has been introduced, employing a terrestrial radio link with some unique features:

- the system performs measurement of airborne radioactivity ***and*** wireless transmission non-stop up to five years with the first battery set
- the radio link is able to cover a radio horizon of more than 100 km (line of sight), conveying all kinds of short data blocks at a net rate of 150 Bd with a bit error rate $< 10^{-10}$
- the system is hermetically sealed and operates from 0 to100 % rH and from -40 to +60 °C without any degradation in performance or distance
- the transmitter is designed to provide ultimate long-term stability: no retuning or any other kind of field service is needed, even after years of operation in the open air
- in order to facilitate licensed operation under any country’s regulation, the system can be tuned to transmit at any carrier frequency between 400 and 500 MHz and is compatible with 12.5 kHz channel spacing (NFM)
- sensor plus transmitter is relatively small and weighs only one kilogram, thus any existing pylon (e.g. from street illumination or public high-voltage lines), or even any prominent tree, will serve as a “perfect” system support (see FIGs. 2 and 4)

IDENTIFYING KEY COMPONENTS UNDER THE ASPECT OF MTBF

Careful analysis of defect-mechanisms in environmental monitoring networks (operating in the field for a number of years) has identified three major sources of failure:

> the power supply: often the cell capacity has expired much earlier than "calculated"
>
> the enclosure: frequently due to water penetration along insufficient seals (ageing), preferably at lids and along cable-feedthroughs and screwholes
>
> the data-link: in many cases on-line connections at remote sites were found to be much less reliable than expected (i.e. promised by the service provider)

One of the most critical aspects in optimising the mean time between failures (MTBF) for an environmental measurement station is the correct choice of the power source. The first step is the decision either for the employment of solar energy, or for operation totally powered by primary cells. Although very attractive at the first glance, the use of solar power is associated with a lot of handicaps.

1.) The product group under discussion is expected to operate in all countries/climates over the world. Consequently, any assumption on the mean solar flux density should also include northern European scenarios (e.g. the installation right between the trees of the famous Nottingham forest). Note: Large solar panels for professional outdoor applications are expensive, and not comparable to their consumer-grade equivalents.

2.) Solar panels need a rigid support with the cells facing to the south. Out in the wilderness, this can be the dominant cost-factor. In the middle of nowhere, these panels are highly attractive for thieves of all ages (although anchored on solid foundations). And they are subject to vandalism as gunfire etc. In contrast: The "all-in-one station" as shown in FIG. 2 can be placed simply by ***hiding*** the device inside a higher tree - a cost-efficient solution. Small is beautiful.

3.) In the course of time, a solar panel will loose a great portion of its initial conversion efficiency. Without regular cleaning, it will certainly accumulate dust, mud, falling leaves, bird's excrements and eventually salt from the seaside. During the winter season it may be covered with snow and ice for several months. And, depending on the vicinity to certain trees, the panel might gather moss over the years. On how much conversion-efficiency can we rely after five years of exposure in the real (dirty) world?

4.) Besides the drawbacks discussed already, there is another risk in terms of reliability: Type and quality of the rechargeable cells employed. We won't discuss the pros and cons of different secondary cell technologies available on the market in this paper. Instead, we would like to ask one short question: Are you still happy with your laptop's battery management?

What to do now, when the sunshine has gone? According to the author's experience, there is only one good advise: Bring down the power requirement to the lowest level possible .... and run the whole station (for several years) with a reliable primary cell system - preferably of lithium type.

With such discovery, there is only one drawback: this low-power-approach demands for a high degree of sophistication, in the data acquisition system, as well as in the wireless link. The later will be discussed in detail.

GENERAL CONSIDERATIONS

In a typical environmental monitoring network, normally a bigger number of remote sensors has to be connected to one base station receiver. Optimising this configuration, two conflicting objectives must be met:

- **Maximum battery lifetime**
  Transmitter power must be kept at the absolute minimum level to provide several years of non-stop-operation in the field with the first battery set (Note: Regular service intervention is a dramatic increase in operational cost)

- **Maximum network coverage**
  In order to establish reliable UHF links to ***all*** sites of a typical environmental data collection network, a link attenuation of -150 dB must be overcome (assuming real-world propagation scenarios)

Hereby it is important to note, that high-gain antennas cannot be used, without compromising the cost-effectiveness inherent to this novel approach: At the transmitter-side, e.g. the durable installation of yagi antennas in a fixed direction would rule out the ”simplicity of placement“ for a big number of telemetric sensors (same reason as with solar panels). And at the receiver, a directional antenna would not really make sense, because normally the wanted signal must be expected from any direction of the sky.

Optimising total system cost, this translates to a more or less “simple“ transmitter design (still providing a clean UHF signal with excellent long-term stability from arctic to tropical environments), but demands for the most sophisticated receiver approach at the base station.

Consequently, the system’s design goal can only be reached, when there is optimum synergy between all the different jobs in the signal processing chain (whether implemented in hardware or software).

For the general system architecture, this urges to merge coherent communication principles, concatenated coding techniques, effective forward error correction and complex time diversity schemes. Each and every component of the radio network is expected to perform as close to the absolute physical limits as possible.

TRANSMISSION PROTOCOL

Under the severe energy restrictions discussed already, only a simplex link can be established. In this case, neither regular data-polling nor verification by handshake can be implemented. Although there is a crystal-controlled real time clock available at the sensor electronics, its deviation over the years will be too large to rely on a preprogrammed timing sequence for all the data exchange in the network. There is only one way out: A modified ALOHA-protocol, i.e. whenever a probe has completed its hourly measurement cycle, a set of three pseudo-random delays is calculated. Next, the fully coded message block is divided in three individual fractions (bursts). Each of these 1.2 sec bursts is released at a different time (randomly distributed within a time frame of 3 x 20 minutes). For the contents of these bursts, see separate chapter on coding further down.

A message block does not only contain the “latest“ update of the measurement data. In the protocol, there are always “historical“ values appended, in case a prior message has been lost. In total, every single measurement point will be transmitted 27 times in an irregular scheme, concluding with a “last trial“ after a period of five days.

Looking at information theory, it is obvious, that such a way of “smearing“ a highly coded (redundant) data stream over a long period of time will provide a maximum of robustness for a simplex link.

MODULATION AND SUBCARRIER

After highlighting the advantages of the staggered pseudo-random time-diversity protocol, now a certain disadvantage must be mentioned: At the receiver-side, there is no information available, at what time a message might be “on the air“. For strong signals this information could be derived from the AGC-hardware in form of a RSSI signal. But this principle would not work properly at the high end of link attenuation’s, to be covered by the approach described here.

In order to facilitate the identification and synchronisation of the wanted signal (close to the theoretical noise margin), a smooth phase modulation, related to a subcarrier of 1.2 kHz was chosen. This signal coding principle is known as “Manchester coding“. Introducing a discrete subcarrier in this manner gives the advantage of focusing the search for the wanted signal on a precisely known modulation component.

CONCATENATED CODING

The ambitious goals in the system under discussion could only be reached by employing concatenated coding. First, convolutional coding of rate 1/2 and a constraint length of nine was chosen for the outer code.

For the inner shell, a Reed-Solomon code (40/180) was selected. The fully coded message block (containing 180 bytes) is transmitted in three separate fractions (of 60 bytes each). The decoder is able to identify the contents in a single fragment, as long as the raw bit error rate is not too high.

Messages arriving with an extremely high bit error rate still can be decoded correctly, when all three fractions are available (ARQ type 2 scheme). Certainly, in this case the fractions must be identified beforehand. This is accomplished by attaching a label, coded BCH (8,128), to each of the fragments, and performing brute forward decoding.

TRANSMITTER HARDWARE

The transmitter design is driven by the attempt to provide a clean UHF signal with excellent long-term stability from arctic to tropical temperatures. Therefore, a third overtone crystal oscillator with temperature compensation was designed (TCVCXO). The maximum frequency deviation is kept below +/- 2 ppm over the temperature range of -40 to +60° C.

FIG. 3: *High performance UHF radio module incl. baseband processor (from left to right: TCVCXO, doubler stages, PA, harmonic suppression filter, antenna rod)*

Constant envelope phase modulation is accomplished by shifting the crystal's resonant frequency a few ppm back and forth (varicap pulling). The maximum carrier frequency deviation is 1.8 kHz. This is equivalent to a modulation index of 1.5 .

Three push-pull doubler stages multiply the signal up to the final carrier frequency in the range of 400 to 500 MHz. Output power can be tuned over a span of 0 to +17 dBm. Normally, the transmitters are adjusted to deliver exactly +10 dBm ERP into the air.

FIG. 4: *Self-contained gamma monitor (incl. radio module) fixed to a light pole. The tubular-shaped metallic construction guarantees hermetic seal over many years. The lambda/4 antenna rod is emitting through the black POM-cap on the top.*

The whole transmitter is compatible with the new European standard ETS 300 113 “Radio Equipment and Systems; Land mobile service“. Thorough baseband filtering (raised cosine) takes care, that the adjacent channel power is less than -70 dBc. Any spurious emissions are less than -70 dBc over the frequency range of 9 kHz to 4 GHz. These limits are much more stringent, than the above mentioned standard requires.

Note: A supplementary duplex communication with the system is provided through infrared-optics, connecting to a PC-laptop.

FIG. 5: *The components of a base station receiver chain: top-unit, isolator, indoor-unit 19", organiser-PC, LAN-port*

GENERAL RECEIVER SETUP

In order to allow for maximum flexibility in the installation, the receiver chain is split into different components, (FIG. 5).

First, there is the top-unit, which should be mounted at the most elevated point available (e.g. a stack or a cooling-tower). Then the indoor-unit must be located within a distance of 300 m to the top-unit. Normally, it is prudent, to insert thorough lightning protection between the top- and the indoor-unit (see isolator in FIG. 5)

When carefully protected, the indoor-unit may be directly installed inside a computer room. When located in a more peripheral building, the indoor-unit may as well be configured to perform as a LAN node. Or it may communicate through a standard telephone modem, when placed in a far-away location.

The entire receiver chain is powered from a 24 VDC supply with 2.5 A (typ.) of current consumption. Normally, there is battery back-up included for several days.

SPECIFIC RECEIVER FEATURES

The receiver is a state-of-the-art triple conversion superhet with two analogue IFs at 21.4 MHz and 134 kHz, and a third (virtual) IF of 20 kHz in the digital domain.

When defining the key-components for the receiver hardware, it is vital to fight for the lowest possible noise figure in the front-end, *BUT* combined with lowest possible intermodulation products (conflicting targets). Of course, an acceptable compromise can be realised with a high effort in preselection filtering, combined with a VHL-classified mixer design.

The omnidirectional antenna, sharp UHF preselection (employing a cavity resonator), a GaAsFET LNA and the first downconversion stage are located inside the top-unit. This unit is hermetically sealed (see FIG. 6). and specified to operate in the open air at the same environmental conditions as the transmitter. The ***total*** noise figure of the top-unit is 1.5 dB, combined with a wide dynamic range of more than 85 dB (SFDR).

FIG. 6: *In order to achieve an optimum noise figure, omnidirectional antenna, preselection, LNA, first downconversion incl. LO, and cable driver are located in a hermetically sealed "top-unit", heading a mast.*

FIG. 7: *The indoor-unit, a heavy 19" plug-in, containing three different system layers:*

a) Analogue IF processing incl. crystal filter for channel-wide selectivity and first AGC (six modules visible upside)

b) DSP system for modulation-specific frequency control, co-channel-selectivity, and matched-filter correlation

c) Embedded PC 486, running Viterbi- ,BCH, and RS-decoder procedures, and extracting signal quality parameters

The received signal is transferred from the top-unit to the indoor-unit at 21.4 MHz via a coaxial cable (see FIG. 5). There is no loss in general receiver performance with cable connections up to the full length of 300 m.

The main effort in recovering the extremely weak signals from the most distant transmitter locations is performed inside the 19" plug-in cabinet, as shown in FIG. 7 .

At 21.4 MHz channel-wide crystal filter selectivity is provided (passband +/- 8 kHz). Next, a fast (analogue) AGC eliminates the signal dynamics, thus resulting in constant IF level over a span of 110 dB in the incoming signal. Typical AGC attack time is 10 ms, release time 50 ms. The residual (noisy) 20 dB of the AGC range is left for the DSP (after ultimate selectivity has been applied).

After the next downconversion, the second IF of 134 kHz is fed through a high-Q LC bandpass and is sampled with 154 kS/s in a 12-bit ADC, thus forming a virtual 20 kHz signal for digital signal processing.

DIGITAL SIGNAL PROCESSING

The digitised data stream is processed with a Motorola DSP 56002. Providing powerful integer arithmetic's for 24-bit operands, and clocked at 80 MHz, this DSP system performs with a respectable number crunching capability (up to 240 MOPS).

The DSP board is also equipped with 1.54 MByte of extremely fast SRAM (BICMOS, 8 ns), organized in 512 k words of 24 bit.

In the DSP-subsystem, the incoming signal is processed in the following steps:

- Data acquisition from ADC
- 1st FIR decimation low pass
- Cyclic 4k-FFT (interleaved)
- Spectral shape identification
- Carrier frequency estimation
- Coarse bit synchronisation
- Block synchronisation
- Fine bit synchronisation
- DPLL initialisation (lock-in)
- Conversion to baseband
- 2nd FIR decimation low-pass
- Matched filter correlator
- Handover to embedded PC

Based on a powerful processing platform, the DSP-implementation of all these complex receiver-functions could be accomplished on a ”close-to-optimum” level. But, without the intensive use of this technology, ”fishing” for the highly-coded burst-signals, totally buried in thermal as well as man-made noise, would have been a hopeless mission.

Only digital processing provides ultimate selectivity by FIR-filter algorithms (shape-factor 6/60 dB = 1.4) as well as modulation-specific AFC functions covering a span of +/- 5kHz. Thus, the receiver system can be made tolerant to a certain amount of long-term frequency deviation in the wanted signal, but still maintaining a high degree of rejection for unwanted signals (working with the same radio channel allocation). With the software techniques developed in this project, a co-channel rejection of +40 dB could be demonstrated for strong interferes, only a few kHz next to the wanted signal.

A coherent phase-demodulation (through downconversion to zero) is accomplished by employing an all-digital PLL with an adaptive first-order IIR-loop filter. For the correct operation on extremely noisy signals, the loop's integration time can be extended up to an equivalent of 128 bit. In such a case, however, much care must be taken for the correct initialisation. Else the PLL will not be locked-in properly, before the end of the (relatively short) message has come.

Finally, the matched-filter correlation technique is applied, and the output is handed over to a PC-486/40 core, installed on another layer of the same cabinet. In this PC, maximum likelihood sequence estimation is implemented (Viterbi). In the next step, BCH- and Reed-Solomon (40/180) decoding is effected (compare previous chapter on coding). After full decoding, any redundance is eliminated, and the incoming messages are stored according to the FIFO principle.

LINK QUALITY ASSESSMENT (LQA)

A very important standard-feature of the new data collection network is the automatic link quality assessment (LQA). In the PC-486, a thorough evaluation of ten different signal properties is effected (for each burst):

Name	**Interpretation:**
PSS	panorama signal strength (wide)
CSS	channel signal strength (narrow)
CFD	center frequency deviation
CPJ	carrier phase jitter (from DPLL)
SNR	signal-to-noise ratio (subcarrier)
CCI	co-channel interferer (discrete)
BER	raw bit error rate (non-coded)
NLB	number of lost bursts (triplet)
UCA	uncoordinated channel activity
LQR	final link quality rating

FIG. 8: *Link operating reliably with only +10 dBm of TX power over 118 km line-of-sight*

All these quality-related parameters are apended to the decoded message and passed over to the SQL data base (see chapter after next). The availability of such records is very helpful in different situations:

At first, during the set-up-phase of a new network, favourable transmitter locations can be found out easily by "trial and error". Note: Using chain and deadlock for provisional fixing, it normally takes a few minutes to move a measurement station from here to there. This kind of mobility is also relevant under the aspect of emergency preparedness, where some measurement locations might be changed in a hurry, in order to gain better "insight" in the course of an incident.

Second, the ***remote*** access to a long history of LQA-data (see chapter after next) is the basis for an effective teleservice worldwide.

A BUILT-IN STANDARD : COST-EFFECTIVE TELESERVICE

No matter, whether a potential customer runs his data collection network around Oslo or close to Capetown, the manufacturer can identify many problems associated with "missing links" out of Frankfurt/Main.

After thorough inspection of LQA-records polled out of a system (located anywhere in the world) the type of malfunction can be classified by trained personnel:

- lithium battery out of power
- defective data acquisition system
- defective transmitter-module
- interfering channel activity, narrowband (either legal or illegal transmitters)
- interfering channel activity, broadband (either EMI or TVI)
- problems related to propagation (reflexion, multipath fading etc.)
- defective top-unit
- defective indoor-unit

Based on this first estimation, it is easy to propose potential remedy or, at least, to suggest action for further investigation.

Being a rather complex system, the question of service-cost can be vital after some years of operation. Therefore, cost-cutting utilities have been designed-in right from the start.

First of all, a strictly modular configuration results in transparency among the different hard- and software components. Additionally, at the rear-side of the indoor-unit, roughly a dozen of check-points is provided. With quick access to the relevant intermediate signals, the customer's first troubleshooting can be very effective already. Even more, when assisted with step-by-step guidance from the manufacturer's help-desk.

Résumé: The implementation of efficient teleservice utilities can reduce service-cost for a data collection network considerably - no matter, whether such action is applied to a system operating in Hamburg or in Hawaii.

A STANDARD SQL-SERVER USED FOR DATA REPRESENTATION

In another (external) PC-Pentium system, called organiser, all messages are "sorted" properly, according to data-source and time sequence. This kind of data base management is done using a standard SQL server. Thus, consistent data records can be polled at any time out of the database, simply by using SQL query commands (DML).

On the same hardware platform, there are different alarm-filters available. Prior to the final deposition in the data base, every new message is checked whether the embedded data contain values exceeding a (programmable) threshold. In such a case, different actions can be triggered, e.g. paging for the radiation protection specialist on duty.

Finally, it is possible to determine a tolerance figure for a certain number of missing protocols. If there was no message, longer than this tolerance figure would allow, then also an alarm can be triggered (function equivalent to a dead-man's handle).

ARBITRARY FAILURE AT THE SENSOR OR TRANSMITTER-SIDE

The environmental gamma measurement system as described here, performs with some unusual features in terms of robustness. Even in the case of (an unforeseen) severe damage to the hardware, the negative effects (total loss of data) can be kept on a minimum level.

In a typical environmental monitoring network, total loss of function at ***one*** measurement location normally is not critical, because there are “neighbours“ that would see the same effects - more or less. As explained in the previous chapter, the system would certainly indicate serial number and position of the defective unit immediately.

In all those applications, where there is a limited tolerance to short-term losses, it is prudent to keep at least one sensor unit in reserve. In case of a failure, it should not take too long, to detach the defective unit and place a spare, whenever the dead-man's alarm has been triggered.
But, in some applications, even a short-term failure cannot be tolerated. Fortunately, due to the "small-is-beautiful“-principle at the sensor-side, redundant placement is a sound solution, that suggests itself. Depending on the individual system's tolerance to failure, the degree of redundancy should be considered right from the start (i.e. with the initial network-planning).

Finally, when a malfunction is restricted to the data-link only (while the data acquisition is performing as normal), not a single value will be lost. Every gamma monitor of the type shown here, will always store ***all*** of its hourly results in a cyclic memory for a period of 18 months. Thus, the user has plenty of time for picking up the missing data “manually“ (under sunny skies).

For this kind of “rescue“, a bidirectional infrared-optical port is provided at the lower end of the tubular housing (see FIG. 4). This allows for conveniant downloading of the instrument's total “history“ into a PC-laptop over a distance up to 10m.

FIG. 9: *Wireless data transmission in a hostile maritime environment. Here: An early-warning system to indicate radioactive leakage from nuclear-powered submarines*

LINK ROBUSTNESS : A WORST-CASE SCENARIO OF DAMAGE TO THE RECEIVER

Finally, let us assume a worst-case scenario: A flash of lightning has hit the top-unit directly: pieces from the dismantled unit are scattered all around. No chance for instant repair!

Even this dramatic event can be managed smoothly. And certainly, without loosing a single data point! On special contract basis with the manufacturer, the user can specify that a complete spare receiver (of same type as in use) is delivered and installed within three days after notice in any European country. Being designed as a turnkey receiver chain, each of the components can be plugged in order to substitute the destroyed piece of hardware within less than an hour.

Next, the user has got nothing to do, but to wait for the repetions of those data that have been lost in the meantime .... the data-gap will shrink, and shrink, and finally, disappear. According to the network's transmission protocol, the last repetition will be effected regularly 128 hours (plus random delay) after the initial acquisition.

Consequently, for a failing receiver system, there is up to five days of tolerance, to "survive" any kind of outage unaffected (i.e. without the need of collecting data from the field sites "manually"). This holds true, even for a worst-case situation. For this network-attribute, we would like to propose the term "soft data restitution" (SDR).

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