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Development of Carrier Signal-Based Overhead Transmission Line Monitoring System for Preventing Line-Ignited Wildfires

Additional submitted attachment is included below.

Whitepaper (unpublished)

Development of a Carrier Signal-Based Overhead Transmission Line Monitoring System for Preventing Line-Ignited Wildfires

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Abstract

This whitepaper proposes a use or reuse of existing, deactivated, or new power line carrier devices as a tool for substation based transmission line status monitoring and intermittent vegetation-caused fault detection to reduce the occurrence of line-ignited wildfire. The carrier based line monitoring system has been tested for aircraft electrical network and has a potential to becomes the most effective tool for continuous, real-time, monitoring of the transmission line to detect and locate the random, unpredictable intermittent faults caused by vegetation. The proposed transmission line status monitoring system would provide an alert for effective utility vegetation control and preventive maintenance. Therefore, it would reduce the root cause of line-ignited wildfires. Several approaches for practical use of power line carrier modems are proposed. A full-scale demonstration project of practical experiments in actual transmission lines or testing facilities would assess the validity of the proposed line monitoring method of carrier-based system.

1. Introduction

Major outages and big damages are caused by, ironically, insignificant and unnoticed intermittent events and missed opportunities to respond to such minor events. Early detection of intermittent self-clearing faults in power line is critical to utility company for electric service reliability and, to some in the east coast, prevention of power arcing caused wildfires. The majority of electric service interruptions and arcing fires occur when trees grow or fall into overhead lines, or when a line makes a contact with other object due to line equipment failure or high wind.

According to a California Department of Forestry and Fire Protection (CDF) statistic, about 2% of vegetation fires are caused by power lines. The CDF fire investigation reports identified several brush fires as power line related fires ignited by power line contact with tree, power line contact with cable, power line detached from insulator contact with adjacent power line, and broken and downed but remained energized power line [1]. In one power line related fire, a 33kV power line, detached from its supporting insulator, swayed under the influence of strong wind and made contact with the adjacent conductor on the same cross arm, which caused arcing that ignited the fire [2]. Another fire was reported to be caused by a downed conductor's ground arcing igniting dry grass [3]. Other power line-caused wildfires share the similar characteristics of arcing as the root-cause initiated by downed but still energized lines or power line touching tree branches under windy condition [4-6]. If these line conditions were early detected in their initial stages, the lines could be de-energized and the fires would be prevented.

Intermittent faults in any wire systems are not permanent faults and, thus, the wire system would behave normally as if nothing happened after the short duration of transient; however, the intermittent transients are the incipient events of a precursor of permanent faults to come. Due to the random and non-reproducible nature of the incidents, the intermittent faults are the most frustrating, elusive, and expensive faults to detect and locate in transmission lines. They are often completely missed by conventional monitoring and detection devices. Monitoring devices installed at substations may not be able to detect such short and small disruption from a faraway location in the circuit. However, if an intermittent fault is left undetected and un-repaired, a major, disastrous, and arcing ground fault might follow that may result in fire and cause property damage and the loss of human life.

To deal with intermittent contact faults in wire systems, a simple approach was proposed which would detect the presence of such faults by injecting a modulated signal or carrier at one location of a line and analyzing the received, causally disrupted carrier upon intermittent event in the line at another location of the line [7]. The essence of the approach is using the communication channel characteristics, in terms of data error rate, of the carrier signal system as an indicator of the transmission medium, electrical wire. The transient caused by the intermittent fault in the wire would disrupt the carrier signal sent over the wire from a transmitter, and thus the carrier signal arriving at the receiver would contain errors. When the transmission errors are found, accumulated, and later compared with a threshold, an alarm or annunciation is activated to alert the system of an intermittent fault [8]. With multiple transmitters installed in towers and poles and receivers in substations, and with proper communication protocols, the intermittent faults can be located by the segment made by transmitters.

This whitepaper discusses a feasibility study of the carrier-based intermittent vegetation-fault detection and the proposition of deployment of the detection system as a status monitoring tool of transmission lines to help utilities with vegetation control and prevention of wildfires caused by power line arcs. The proposed transmission line monitoring system is expected to enhance utility's capability in identifying otherwise unnoticeable intermittent events and latent defects and in preventing them by early corrective action from developing into permanent vegetation faults that may cause destruction, explosion, or wildfire. Even though the traditional carrier system loses its position as a pilot for relaying and tele-protection and is being replaced by fiber optic communication, it can now find a new life playing a critical role of detecting intermittent vegetation-contact events in the line. The application of the simple but ingenious carrier system could become a valuable asset for reducing the root cause of line-ignited wildfires.

2. Intermittent Fault Detection by Power Line Carrier System

This approach of identifying intermittent faults in a wire system was developed by the author originally for aircraft electrical and sea vessel electrical systems [7, 8]. The new approach ingeniously utilized the noise interference caused to make signal/data errors in power line carrier communication. The transient caused by an intermittent fault in the wire would disrupt the carrier signal sent over the wire from a transmitter, and thus the carrier signal arriving at the receiver would contain errors. When the transmission errors are found, accumulated, and later compared with a threshold, an alarm or annunciation is activated to alert the system operators of an intermittent fault [8]. With multiple transmitters installed in towers and poles and receivers in substations, and with proper communication protocols, the intermittent faults can be located by the segment made by transmitters.

The principle of using a carrier signal in intermittent fault detection comes from the idea that random and unpredictable intermittent events are to be detected only when the event is active. An ideal solution would be to superimpose a signal on the conductor that can be causally influenced by any event on the conductor. The approach applies a carrier signal on the wire system which is under observation at all the times, and utilizes the disruptions made in the carrier signal caused by any event on the wire by random, unpredictable intermittent faults. One such scheme is the low-frequency power line carrier signal which has been used for protective relaying and protection system communication purposes in utility industry. The next section describes a low-frequency carrier system and the evaluation of the proposed message-error based intermittent fault detection using the prototype.

Low-Frequency Carrier System

A carrier wave or carrier signal is a waveform of a specific frequency in a communication channel that is modulated with an input signal to be transmitted for information exchange. A well-known carrier communication method, power line carrier communication, is a method of transmitting data through existing electrical lines alongside electric power. This traditional application of using narrowband power line carrier can be found in remote monitoring and in some applications in the development of a smart motor that combines both the power and control lines into a single wire [9]. Related to fault detection, Taylor and Faulkner proposed direct-sequence spread-spectrum modulation on power line carrier, and outlined optimal signal processing techniques and frequency domain correlation techniques for an on-line test on high voltage lines [10]. Lately, a slightly different use of spread spectrum was reported from the research, detecting avionic wire problems [11].

However, since it is believed that an intermittent fault in the line would disrupt the carrier signal, a simple carrier signal modulation scheme like frequency shift keying (FSK), which varies the frequency of the carrier signal according to the value of each bit in the digital data stream transmission [11], would serve the purpose of determining carrier signal or message errors. In practice with the FSK scheme, transmitted over electrical interconnect system, the carrier signal would not be disrupted if the medium is clean, healthy, and quiescent, and therefore there would not be carrier/message error in the received data. However, when the medium is impacted by intermittent events such as line intermittently touching tree branches, the carrier signal would be disrupted, which in turn results in error in the data stream or message. In other words, the erroneous information or missed information compared against the correct information between a transmitter and a receiver would indicate that the carrier signal communication channel, the segment of the electrical wire in an electrical system, is faulty and is in contact with vegetation or an object. Also, an open circuit can be easily recognized by the missing data stream for a period of time in the receiver.

Fig. 1 reproduces the oscilloscope-captured impulse spikes, which were generated in an energized power line by teasing a knife blade switch, making sporadic contacts between supply and ground wires, with carrier signals in transmission. In the figure, with the background of sinusoidal carrier signal of around 130 kHz, it is clearly seen that the teasing switch impulse spikes disrupt the carrier signal.

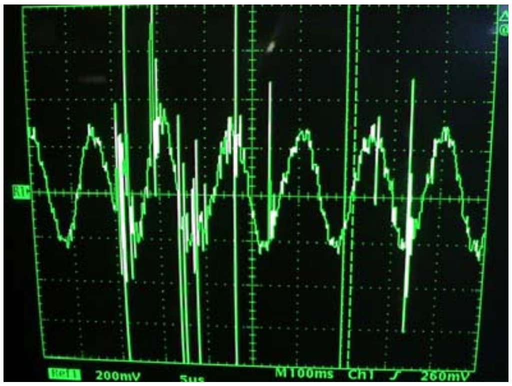

Fig. 1. The impulse spikes generated by teasing a knife blade switch, disrupting the power line carrier signal transmitted in the parallel configuration in an energized power circuit.

Fig. 2 shows the message streams (upper trace) and their corresponding carrier signals of FSK modulation (lower trace) during the normal condition of the circuit. At the receiver side, the carrier signal is FSK demodulated and the message is reconstructed. If the received data stream of the message matches with the data stream from a transmitter, it can be said that the communication medium, the wire, is not experiencing a disruptive event. In such quiescent, non-faulted circuits, it is expected to have the identical digital data streams of both transmitter (upper trace) and receiver (lower trace) as depicted in Fig. 3. The time shift between the two data streams, determined by the bit rate of the carrier signal modem, is clearly seen in the figure.

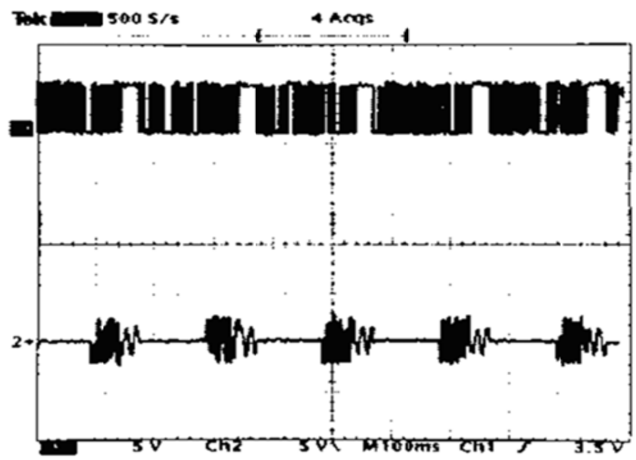

Fig.2. Digital bit stream generated by Transmitter (upper trace) and the FSK modulated carrier signal over the wire (lower trace).

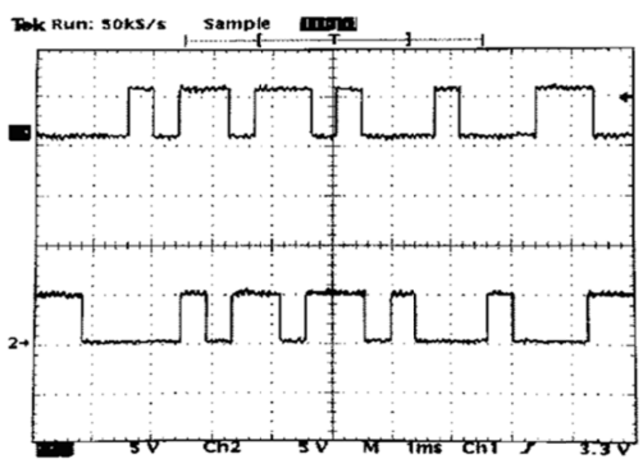

Fig.3. The same digital bit stream of Transmitter (upper trace) and Receiver (lower trace) sides under normal condition.

When the carrier signal channel of a wire is disrupted by intermittent faults, the signal over the wire would be corrupted. In Fig. 4, the upper trace shows data streams generated in the Transmitter, and the lower trace shows the modulated carrier signals over the wire, which were disrupted by a staged, intermittent fault condition. The carrier signals are much different from those in Fig. 2 of the normal, non-faulted circuit condition. Thus, the received data stream would be also different from the transmitted data stream. Fig. 5 shows the impacted received data caused by the intermittent contact fault in the receiver side (lower trace) against the data stream sent from a transmitter (upper trace). The received data in lower trace is starkly different from the transmitted bit stream of the upper trace. As illustrated, by analyzing the received data stream against expected data, abnormalities in the circuit can be detected in real time.

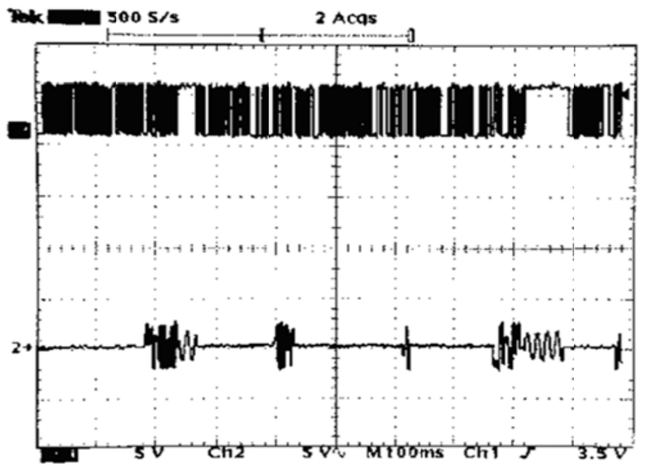

Fig.4. The generated bit stream (upper trace) from the Transmitter and the disrupted carrier signal over the wire (lower trace) caused by teasing spike noises.

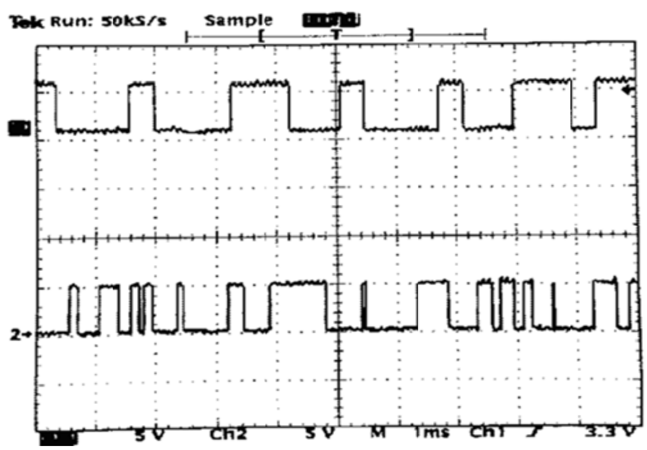

Fig.5. The difference between the transmitted digital bit stream (upper trace) and the received (lower trace) under a fault condition.

Feasibility of Low-Frequency Carrier System for Intermittent Contact Fault Detection

To detect discrepancies between the transmitted and received message streams, two types of errors were defined: byte error and bit error. A byte error occurred when a particular byte of data received was different from the corresponding byte sent, regardless of the number of bits erred and their locations in the byte. A bit error occurred if a bit in a particular byte received was different from the corresponding bit of the corresponding byte transmitted.

After the initial run for baseline establishment, the carrier transceivers in the circuit setup were tested under intermittent fault/spark conditions, and the two types of byte errors were analyzed. For each test of the fault condition and error analysis, 1000 message streams were transmitted and received over the circuit while the motorized switch mechanism was making sporadic contacts with a copper strip conductor. For each run of the test, multiple-byte errors and single-byte errors were counted. From these, the error rates for both were obtained by dividing each count by the total number of bytes transmitted/received. Then, multiple runs produced average values for two types of byte error rates: average multiple-byte error rate (AMBER) and average single-byte error rate (ASBER). It was found that the ASBER was much better detection predictor.

The feasibility tests of the carrier transceiver prototype with the arc/spark generation circuit demonstrated the promise of the carrier message error approach in detecting intermittent faults in electric power lines. Further tests showed a consistent discriminatory difference in the ratio of the error rates, especially of ASBER, between the staged intermitted contact-fault conditions and the baseline.

3. Suggested Utilization of Substation Carrier Systems for Transmission Line Monitoring

The carrier-error based line monitoring system that was tested for feasibility can be applicable to any transmission lines in utility systems, either by utilizing the existing carrier systems in the substations which are being used for tele-protection of the line, or by reviving the decommissioned carrier systems that were once used for a tele-protection system, or by installing a new carrier system dedicated for this line monitoring purpose. Today, carrier systems are being removed from service and replaced by dedicated fiber-optic communication systems, and they are being disconnected from protective relaying systems. These idle, yet installed carrier systems are the best candidates to be utilized for realizing the line monitoring system for intermittent contact fault detection. The only additional equipment required at each carrier system is a PC to transmit/receive message streams through the carrier system, analyze the error rates, and detect intermittent faults and latent defects in the transmission line. To locate the intermittent contact fault, multiple transmitting carrier systems can be installed in towers or poles while keeping just one receiving carrier system in a substation. An industrial grade PC is best, as it will need to run for extended periods without resets or other human operator intervention. We will discuss practical suggestions of the carrier-error based line monitoring system for utility companies for vegetation-contact faults. The chapter describes first a study of transmission systems to maximize the benefit of the systems, followed by how the carrier systems can be used and what diagnostic information from the carrier systems may be utilized for the proposed carrier-error based line monitoring system.

Transmission Line Study

Utilization of the existing or new carrier system starts with careful study of the make and model of the system, and the transmission lines of greatest interest to wildfire prevention. This will determine the benefits of early detection of tree contact, foreign object contact, and downed/energized condition of the line. Understanding the existing carrier system deployed on transmission lines is an important first step for correct and optimal utilization of the carrier systems for line monitoring use.

The initial investigation should start from the selection of a transmission line which is at higher risk of animal or vegetation and/or strong wind. Once an area is chosen, then the carrier systems in each of the substations of the area need to be studied to determine the manufacturer, model, and present usage of the carrier system. The system can be set up for use on a line with more than two terminals, as will be discussed later. In the utility industry, many old carrier systems have been used mostly for tele-protection purposes. Presently, many of these old carrier systems are decommissioned in place, and have been left deactivated.

For their use for tele-protection for a transmission line between two substations, a carrier system at a substation transmits a carrier signal via a tuning circuit into the line. The carrier system at the other end (another substation) receives the carrier signal via its own tuning circuit, for intended keys for “Trip or Guard” control, for example. Periodically or simultaneously in duplex mode the carrier systems switch their functions, from transmit to receive, and vice versa. Carrier systems applied for transmission lines are typically used for current or current differential relaying purposes for protection coordination, to find and act only on faults inside or outside of a protection zone. Two carrier systems are used, each disposed at either end of a line under protection coordination, and signals are exchanged between the two, either allowing relaying action or blocking it. However, the carrier based protection systems were gradually replaced by wired-communication systems due to frequent errors in carrier communication, which were caused, most notably, by corona noise. Paradoxically, this is exactly why carrier systems can be used for intermittent contact fault detection, which may cause communication noise and transients errors along the power line.

Diagnostic Features of Carrier Systems

A carrier system designed for high-speed transfer-trip relaying for tele-protection is configured as either a transmitter or receiver, but one transmitter and multiple receivers could be stacked together at a substation for operation on a line when the line is connected to more than two substations. For signal communications between the two, high frequency (HF) signals were provided which could travel over the power line with a modulation method. In addition to this main feature, there were other, diagnostic, features available for the carrier system itself. They were intermediate frequency (IF) signals, carrier noise status, system operational status, etc. More specifically, a receiver was comprised of several modules, each having front and back panel terminals for additional measurement and/or diagnostic uses, including filter, oscillation, signal noise and carrier level monitoring. These diagnostic features can be utilized for the proposed carrier-error based line monitoring system for incipient fault detection systems, without disrupting their function for tele-protection. Both functions will coexist gracefully.

Practical Approaches for Carrier-Error Based System Implementation

Considering the different carrier products and their usage in utility systems, we suggest three ways of realizing the carrier-error based line monitoring system for utility companies under different time and financial constraints or urgency. First, we suggest a method of co-utilizing the existing, active carrier systems presently dedicated for tele-protection purpose. Next, we suggest a method of utilizing currently deactivated (but installed), decommissioned carrier systems. Lastly, we discuss implementing a carrier-error based line monitoring system with a new carrier system, using off-the-shelf contemporary technology. However, the best option would be a complete new installation with much simpler carrier system dedicated just for transmission and receipt of simple digital message.

Utilization of Presently Active Carrier Systems: The simplest approach, utilizing a currently active carrier system, is to tap into the noise information on the signal, which is available from signal noise diagnostic modules of the carrier system. From the module, the following three parameters of carrier noise are usually available via a modest signal capture device and a PC: spike output, noise output, and level output of the carrier signal, as measured at the receiver system. This carrier noise information is useful for carrier-error monitoring, since the disruption along the line, caused by intermittent vegetation contact would affect the carrier signal and thus the carrier noise. This approach of tapping the existing carrier systems is an economical and simple option for immediate applications. However, the rudimentary information of level and level change may not be sensitive enough for effective carrier-error monitoring. Another problem with this approach is that, since there are carrier systems only at substations, the exact segment of fault location is impossible. For smaller location segment, new transmitting carrier systems have to be installed between substations.

Utilization of the Installed, but Deactivated Carrier System: As stated above, carrier systems in the transmission lines have been decommissioned and presently are being replaced by dedicated fiber-optic communication systems. These idle carrier systems are the best candidates for realizing the carrier-error based line monitoring system. The inactive carrier systems can be utilized as a complete transmitter and receiver system for a transmission line with all the level and RF and IF information of the carrier signals available for analysis. In addition, unlimited access is available to the diagnostic terminals and modules, and to the interior signal points. This will enable us to select and encode/decode the message to be delivered and received over the power line. Of course, the trip/guard message information can be continuously transmitted and received as required for message error determination. However, as above, the problem with this approach is that, since there are carrier systems only at substations, the exact segment of fault location is impossible. For smaller location segment, new transmitting carrier systems have to be installed between the substations.

Installation of New Carrier Systems: When the transmission system does not have carrier systems, or there is a desire not to interfere with an existing carrier system, a new carrier system can be installed for a carrier-error based line monitoring, for any line between two substations, two poles, or two towers, each equipped with a tuner circuit and a wave trap. The biggest advantage of this option is the freedom of line and location choice, and adoption of much simpler carrier systems dedicated for message transmission without tele-relay functionality. However, the biggest hurdle is the required cost of the carrier systems, additional tuners and couplers, and the installation of the components.

Benefits of Carrier System Utilization for Line Monitoring
As illustrated in Fig. 6, carrier systems, along with PCs and couplers and line traps ("wave traps") can conveniently make a carrier-error based system for monitoring transmission lines for preventing line-ignited wildfires. The suggested approach, utilizing either active carrier systems or deactivated ones for carrier-base line monitoring, may be applied to any utility system. The proposed approach of the carrier system utilization holds promise for ready application to any transmission line.

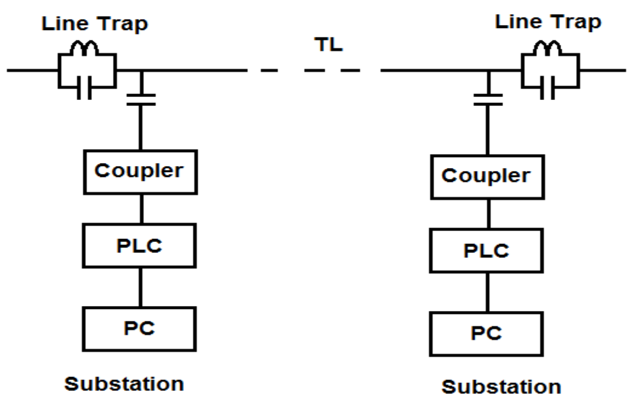

Fig. 6. A proposed configuration for two-terminal transmission line monitoring.

Even though traditional carrier systems are losing their function as a pilot for relaying and tele-protection, and are being replaced by fiber optic communication, they may now find new lives, playing critical roles detecting intermittent contact events in transmission lines. The proposed transmission line monitoring system can enhance a utility's capability for identifying otherwise unnoticed intermittent vegetation contacts, and in preventing further harm by early corrective action. The application of this simple, but ingenious, carrier error based system could become a valuable tool for reducing the root cause of power line-ignited wildfire. With multiple transmitters (TX) installed in towers and poles and receiver(s) (RX) in substations, and with proper communication protocols, the intermittent faults can be located by the segment made by transmitters as illustrated in Fig. 7.

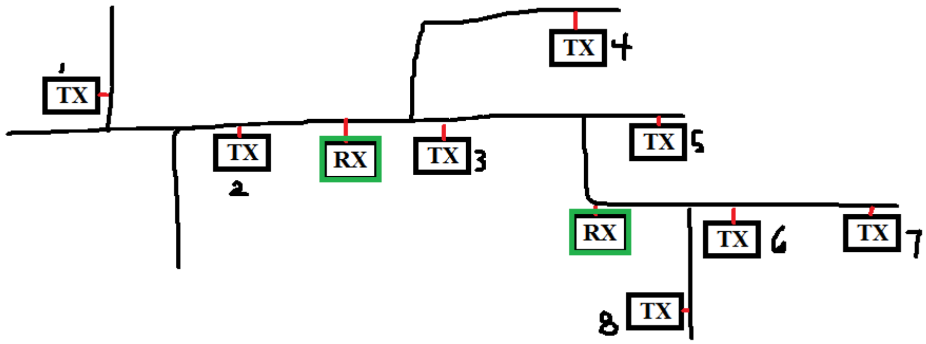

Fig. 7. Multi-Transmitter Carrier System Configuration for Segmentizing Transmission for Locating Vegetation-Contact Events.

4. Conclusions

The majority of electric power arcing fires occur when trees grow or fall into overhead lines and when a line make a contact with other object due to line equipment failure or high wind. Early detection of intermittent vegetation contact faults in the overhead power line is critical to utility industry for reducing line-ignited wildfires. The proposed transmission line status monitoring based on low-frequency carrier system would provide an alert for effective utility vegetation management and preventive equipment maintenance and thus reduce the root cause of outages and decrease wildfire. The carrier-based line monitoring system can provide the most effective tool for continuously, real-time, watching the line for detecting and locating the random, unpredictable intermittent contact events, the harbingers of disastrous electrical failures and fires. Additional expected benefit of the proposed carrier-based line monitoring system can be found in its decision assist role on de-energizing object contacting or downed transmission lines. A full-scale demonstration project of practical experiments in actual transmission lines or testing facilities would assess the validity of the proposed line monitoring method of carrier-based system.

5. References

[1] “Percent of fires by cause-statewide”, CDF Redbook, California Department of Forestry and Fire Protection. 2006.
[2] 2007 Fire Investigation Reports, CA-CDF-010432 (Witch Fire). California Department of Forestry and Fire Protection.
[3] 2007 Fire Investigation Reports, CA-BDU-011653 (Martin Fire). California Department of Forestry and Fire Protection.
[4] 2007 Fire Investigation Reports, CA_BDU_011627 (Cajon Fire). California Department of Forestry and Fire Protection.
[5] 2007 Fire Investigation Reports, CA-CDF-010484 (Guejito Fire). California Department of Forestry and Fire Protection.
[6] 2007 Fire Investigation Reports, CA-CDF-010502 (Rice Fire). California Department of Forestry and Fire Protection.
[7] Charles Kim and Nicholas Johnson, "Detection of Intermittent Faults in Aircraft Electrical Wire by Utilizing Power Line Communication," Proceedings of the 9th joint FAA/DOD/NASA Conference on Aging Aircraft, March 7, 2006. Atlanta, GA.
[8] Charles Kim, “Detection and Location of Intermittent Faults by Monitoring Carrier Signal Channel Behavior of Electrical Interconnection System,” Proceedings of 2009 IEEE Electric Ship Technologies Symposium p. 449-455. April 20 - 22, 2009. Baltimore, MD.

[9] Chun-Hung Liu, Eric Wade, and H. Harry Asada, "Reduced-Cable Smart Motors Using DC Power Line Communication", Proceedings of IEEE International Conference on Robotics and Automation, vol 4., pp. 3831-3838, 2001.
[10] V. Taylor, and M. Faulkner, "Line Monitoring and Fault Location using Spread Spectrum on Power Line Carrier", IEE Electronics Letters, vol. 143, issue 5, pp. 427-434, Sep 1996.
[11] I. Hakki Cavdar, "Performance Analysis of FSK Power Line Communications Systems Over the Time-Varying Channels: Measurements and Modeling", IEEE Transactions on Power Delivery, vol. 19, issue 1, pp. 111-117, Jan 2004.

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