Software Defined Radio (SDR)

The Holy Grail for Interoperability

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ABSTRACT

SDR: The Holy Grail for Interoperability

A prolonged endeavor among the Class I railroads has been a wireless communications platform that is both interoperable among their existing legacy systems and that will also embrace new technologies without extensive new capital outlays. A Software Defined Radio (SDR) on the locomotive is the answer to that endeavor.

An SDR uses software-programmable digital signal processing (DSP) techniques to dynamically change its fundamental characteristics such as frequency, modulation, bandwidth and data rate. This capability allows a single radio on a locomotive to transform itself into whatever type of radio is needed to communicate with the infrastructure environment around it.

This paper describes the design and packaging of an SDR that is capable of operating in low band VHF, high band VHF (data and voice), ATCS, 802.11b and other auxiliary communication channels, all interconnected through an Ethernet bus to an embedded communication management unit (CMU).

An SDR with multiple communication channels, along with embedded processors, allows more intelligence to reside in a field device to support direct communications between locomotives in a train consist, train to control office, and peer to peer communications with other network nodes within its RF range, essentially creating a mobile “mesh network”. Applications such as, proximity warning, locomotive control, compliance with authority limits, consist integrity, location notification, local situational
awareness, track integrity, wayside detector devices, switch position notification and crossing monitoring will all benefit from an SDR implementation.

Preliminary test results of a prototype SDR operating on the existing infrastructure of the BNSF Beardstown Subdivision will be presented.
“The significant problems we face cannot be solved at the same level of thinking we were at when we created them.”

- **Albert Einstein** –

**An Opportunity for Transformation**

The implementation of a train control system that will support significant operations efficiencies inevitably requires a robust wireless connection that is affordable, interoperable, and reliable to be successful. Up to this point no serious effort has been made to implement a true train control system across a major property partly because those criteria have not been fully met. (1) The delay may be fortunate in that the rail industry has a window of opportunity to rethink the train control architecture of the locomotive and the entire train control system before implementing a solution. The opportunity to start with a clean slate and incorporate today’s emerging technologies and methods into fundamental improvements in the cost and operation of train control is real and compelling.

Changes in technology and past experience, including a great deal of anecdotal data concerning failed and over budget train control projects, seem to indicate that a decidedly different approach is warranted. In response to that concern, BNSF has stepped back to take another look at the architecture and made an effort to reimagine the solution looking back from a future perspective. Particular consideration was given to the limited options available, the cost of continuing to wait on a solution, the shortcomings of existing solutions and the fact that train control will continue to evolve.
The resulting wireless architecture solution addresses these issues and is significantly
different than the traditional train control architecture represented by ATCS/PTC.

The proposed solution addresses wireless bandwidth issues by narrowing the
discussion to those wireless options reasonably available to the railroads for train control.
(Table 1) The solution however is open enough to allow the flexibility for the
architecture to evolve and incorporate new technologies and applications. Specifically,
the new solution proposes the introduction of three new and structurally different
concepts; Peer to Peer Communications, Software Defined Radio (SDR) and networking
the locomotive consist. These elements have the potential to change the way we build
and operate a train control system and provide the cost and reliability benefits we need to
build a compelling business case. The proposed equipment and software not only
changes, but transforms the overall train control architecture by introducing new more
efficient operating concepts and by building in the flexibility to adapt to future changes.

The business case for train control has continued to run into a cost/benefit
problem since the first trial in the late 1980s. There have not been enough benefits for
any one application to drive the installation of a train control system because the initial
basic cost to reach the levels of reliability and ubiquity required is too high to be
compelling. The European train control solution ERTMS, for example, takes the current
office centric architecture to its zenith with high speed trains but with an infrastructure
expense that appears to be prohibitive to North American Railroads. (2) In contrast, the
new solution proposed here significantly changes the architecture on the locomotive and
throughout the infrastructure with the objective to provide high levels of performance at
lower cost.
To move forward into a train control environment, reliability must be enhanced to build confidence in the train control system while, at the same time, the cost of the locomotive installation and infrastructure must be reduced to a level that promotes rapid implementation. By building the reliability and performance into the architecture rather than the individual components this proposed solution can bring these diverging cost and performance goals into line and also increase the level of reliability and redundancy to support a compelling business case for a train control wireless infrastructure.

**The Architecture**

Communications to and from trains is in the process of being transformed from a voice centric environment to a data centric environment. This environment coupled with other technologies can line up with the FRA’s vision of “Intelligent Railroad Systems” that “will improve safety, security and efficiency of freight...railroads”. (3) Access to these benefits will require changes in the wireless telecommunications infrastructure. This discussion will focus primarily on the communications changes required on the locomotive to achieve the cost and productivity objectives for the enterprise and the infrastructure alternatives that will affect the overall telecommunications capabilities.

The implementation of a compliment of new electronic elements operating within the locomotive consist have the potential to provide significant value both in cost reduction and higher levels of productivity and reliability. The major new elements include a Software Defined Radio (SDR), a Communications Management Unit (CMU) and a wireless ad-hoc network for the locomotive consist. These elements must be in place and working in concert before the expense and productivity benefits can be fully
realized. The overall goal for this architecture is to make a significant improvement in functionality, redundancy and reliability while continuing to control costs at near expected replacement levels and retain the flexibility to support the train control investment into the future.

**Key point #1:** reliability in this architecture is a product of the architecture more so than the reliability of the individual elements, essentially increasing the reliability of the overall infrastructure while lowering the reliability requirements of the individual elements and therefore the overall cost of the system.

The first element is a Software Defined Radio (SDR). An SDR is a radio in which software modules running on a generic hardware platform are used to implement radio functions such as the generation of the transmitted signal at the transmitter (modulation) and detection and demodulation of the received signal at the receiver. This allows a generic radio hardware platform to function as one of many different types of radios, to transition from one type of radio to another, and to be upgraded (through software updates) to function as a new type of radio in the future. An SDR with front ends (antennas and amplifiers) that operate within the RF bands controlled by the railroads will provide a generic radio platform on each locomotive. The proposed locomotive communications package (FIG 1) would equip each BNSF locomotive with a minimum set of radios that includes two SDRs. This communications package enhances interoperability by providing access, via the SDR, to the communications and train control networks covering the territories the locomotive would traverse on home and foreign railroads. The SDR software would reconfigure the radio to provide a reliable RF
link; selecting between low band VHF, high band VHF and 900MHz UHF, and using a suite of modulations to match the local infrastructures.

The second element is the Communications Management Unit (CMU). A CMU is defined by the draft version of the AAR Railway Electronics Task Force (RETF) Railway Communications Network Specification as “a set of functions on a remote network that manages one or more wireless communications links.” (4) The CMU performs link management, message queuing, and message routing functions for applications resident on a locomotive. The CMU provides the information traffic management on board the locomotive for both voice and data to optimize routing and prioritize access. The CMU function is central to the transfer of information both on and off the locomotive, the moving of information between applications and the transfer of voice and data information within the locomotive consist. The proposed locomotive communications package design distributes CMU functions within both SDRs on the locomotive, increasing the overall reliability of the system by providing a redundant set CMU functions on each individual locomotive. This design also allows a single SDR to operate alone on other equipment. (high rail, switch engine, on track equipment, etc.)

The third element is ad-hoc networking. The proposed communications package uses Wireless Local Area Network technology (i.e. IEEE 802.11) to link the data networks (FIG 2) on each locomotive into a single ad-hoc network. [Note: This may alternatively be accomplished with power line data network products using a pair of conductors on the MU line as a physical medium but may not provide the opportunity to skip over a locomotive whose network is not performing.] The ad-hoc network architecture allows the CMU in the lead locomotive to route voice or data information
through radios and/or application processors in any other locomotive in the consist, essentially creating a single mobile network node with a multiple radio and processor elements.

A CMU in a locomotive consist that has an Ad-hoc network can use radios on different locomotives in the same band either in full duplex mode (one radio transmitting while another radio is receiving) or simplex mode on separate channels with better message reliability than a full duplex radio on a single locomotive, due to improved channel isolation from the send and receive antennas being located on different locomotives.

The mobile node can also provide increased levels of redundancy for all the radios and other electronic elements in the consist by allowing failed or underperforming elements to be replaced electronically under CMU control [Note: The ability for a CMU to detect failed components and route messages through redundant/backup components is, at this time, beyond the scope of the RETF Network Specification efforts]. This redundancy results in an improvement in overall reliability of the locomotive consist communications capability. Ad-hoc networking reduces overall costs by providing a rich set of redundant elements while maintaining a rather Spartan, cost effective, installation on each locomotive. It also enables the exchange of locomotive information useful to certain applications (e.g., locomotive consist confirmation and traction motor cut out status for better PTC predictor performance).

These three major functions, the SDR, CMU, and ad-hoc networking, may be located in separate boxes on the locomotive or integrated into existing equipment, but all these functions need to be present and working in concert to achieve the greatest cost and
productivity benefits. Two of the elements, the SDR and CMU, are currently under development, but the third, ad-hoc networking, uses off the shelf hardware and is in the conceptual stage with regard to some finer points such as security, positive locomotive identification and methods for linking and unlinking the consist network. Ad-hoc networking should be given immediate consideration for funding to complete the proposed locomotive communications package.
**Key point #2:** The locomotive consist infrastructure is designed to be highly redundant but with a lower number of individual elements on each locomotive to keep costs down.

The Peer to Peer communications, while not a locomotive hardware issue, is a vital part of the overall train control architecture. Peer to Peer communications uses a direct communication link between the locomotive and wayside equipment that an office server can monitor. This system uses broadcast messages that have specific origin and destination addresses but can be heard by other receivers in the area. The Peer to Peer communications architecture allows the locomotive consist to remain aware of its immediate environment and transfer operations critical messages directly to and from the wayside devices or other vehicles. Train control functions that require interaction (data transfer) between a locomotive and the wayside are conducted over an RF peer to peer link in which messages from the locomotive are addressed and transmitted directly to the wayside device, without being routed through a fixed RF office centric network. Messages from a wayside device to a locomotive are likewise transmitted in an RF peer to peer manner. The use of an RF peer to peer link reduces the RF traffic since the fixed network is not relaying the message. Base stations are able to receive the messages being transmitted over the RF peer to peer link and route those messages to the office, allowing the office to monitor and intervene to rectify a traffic flow problem or send control directives.

The peer to peer communications architecture creates an additional logical layer of control by maintaining the office connection for global control and creating an additional
local control layer on the locomotive using peer to peer communications to maintain an awareness of its local environment and a capability to react to traffic issues.

The Peer to Peer communications architecture improves the reliability and efficiency by not only providing redundant logical layers of control but by removing a significant amount of latency from the delivery of operations critical messages. For example, messages to and from wayside equipment can be handled in tens of milliseconds rather than the seconds inherent in traditional architectures like ATCS.

The peer to peer architecture requires a more controlled environment than the traditional networks like ATCS/ARES/PTC that can only be provided in a TDMA based simplex architecture. This is a significant departure from traditional designs but has little effect on the control messages between the office and the locomotive and therefore the transition from a traditional office centric network to a peer to peer network and back should not create significant issues for the locomotive equipped with the proposed locomotive communications package.

**Key Point #3:** Relative to traditional approaches like ATCS, Peer to Peer communications has potential to significantly improve radio spectrum usage with fewer messages, reliability by enabling multiple layers of control, performance by removing latency in critical message transfers and functionality by enabling additional features like proximity warning.
**Key Point #4:** The proposed locomotive package will support traditional office centric architectures liked ATCS spec 200 and allow that architecture to migrate to VHF where desired while continuing to support a Peer to Peer capability where that makes sense including simultaneous operation with the traditional architectures.

**Locomotive Communication Package Design Issues**

1. **Urgency** – The likelihood of a train control project beginning within the next two years will be significantly increased if a more cost effective telecommunications infrastructure can be implemented as part of the project. An SDR operating within selected train control RF spectrum would be a major factor in facilitating the implementation of train control by lowering the cost and should also meet the performance criteria for the expected life of the program. The concurrent development of an ad-hoc networking solution for the locomotive consist will also improve the likelihood of a train control implementation by improving the system redundancy and performance while reducing cost relative to a discrete non-networked solution.

2. **Spectrum Bands** – The primary value of an SDR lies in its ability to emulate a variety of radios, reconfigure between them quickly and update or add radio modulation schemes through software downloads. There are design tradeoffs that always exist with any technology and the SDR is no exception. The rationale for the particular design choices made for the SDR are detailed in the following discussion of the SDR and the other elements that amplify the benefits. The SDR, for example, cannot reach its full potential
for cost savings without the ability to network with adjacent locomotives to share radio and applications infrastructure so those elements are included in the discussion.

A Software Defined Radio can be designed to tune over a wide range of frequencies but incurs a large cost penalty for implementing that capability using present technology. Present antenna designs also incur cost and/or performance problems tuning over the same large range of frequencies. An SDR using discrete front ends and antennas matched to the spectrum bands significantly mitigates these performance and cost restraints. The SDR using discrete front ends and antennas in concert with the CMU and Ad-hoc networking can provide the redundancy and upgrade capabilities that reduce cost and improve performance relative to single purpose radio solutions.

There are only a limited number of candidate bands available under the exclusive control of the AAR. (Table 1) The frequencies are limited to the six channel pair ATCS allocation at 900MHz, 3 channel pairs at 450MHz, the recently purchased 5 channel pairs at 220MHz, the 182 channels in high band VHF at 160MHz and a significant number of channels not under exclusive control of the AAR but widely available in low band VHF at 40-50MHz.

Two of the available bands, 450MHz and 220MHz, do not appear to add enough value at present to justify a separate discrete front end and antenna to provide access via SDR. The channels at 450MHz are dedicated to Distributed Power (DP) and End of Train (EOT) applications over much of North America and are utilized heavily already. This essentially eliminates most of the benefit for including 450MHz in the SDR. The 220MHz channels are dedicated to remote controlled switching operations which virtually eliminate the advantage for inclusion into an SDR. The remaining bands
(900MHz, 160MHz, 40-50MHz) are viable candidates for an SDR to support train control and data/voice operations.

The ability to network between locomotives is a product of off the shelf technology using the 802.11(x) standard. The 802.11a is proposed as the primary bridge between the locomotives in a consist. The 802.11a band is also adjacent to the Dedicated Short Range Communications (DSRC) band that is exclusively dedicated to transportation. DSRC could be used if interference becomes a problem with the off-the-shelf 802.11a unlicensed equipment. Interference is unlikely however due to the proximity of the transmitter/receivers and the directional nature of the antennas on the proposed installation. The 802.11a should consistently provide over 10Mbps to transfer information within the node. A single 802.11a radio would be part of the locomotive Ethernet infrastructure and not part of the SDR. [Note: Power line data communications using the MU train line as a physical medium will not have these external interference problems.]

The high speed, short range link on and off the locomotive would use 802.11b/g for data transfers within terminals and locations where a ground based high speed access can be built out cost effectively. The 802.11b/g radio would also act as a backup to the 802.11a link in case of failure. This configuration allows multiple backup paths between locomotives and on/off the locomotive consist to enhance architectural reliability.

The development of cellular and satellite capabilities is assumed to be too complex and expensive for inclusion in an SDR. The cellular radio environment in particular is evolving rapidly and off-the-shelf equipment is inexpensive and can be networked with the SDR easily via an Ethernet connection. Consequently, there is
virtually no advantage for building a cellular radio into an SDR. The range of satellite solutions vary significantly with regard to technology and hardware. Satellite solutions are complex and often proprietary and can also typically be networked through an Ethernet connection. Satellite service is typically expensive relative to other alternatives available to railroads. Their inclusion in an SDR is therefore of questionable value.

The general consensus of the rail industry is that commercial services will make considerable inroads into the wireless architecture of the railroads and that commercial wireless services will capture the majority of the non-control data where coverage exists. Therefore, the business case for inclusion of additional private spectrum bands that would require new radios and ongoing costs to access them does not seem viable and therefore additional bands are not included in the SDR design.

The overall design is intended to provide a package that not only provides a means of going forward with train control in the near future but would be flexible enough to respond to whatever minimum requirements for interoperability are established in the future for operation on foreign railroads. The likelihood of the industry eventually adopting an interoperable standard for train control that would not be supported through a software upgrade within this package is fairly low.

*Interoperability* - The conflicting goals of technology change and maximizing value from legacy systems must be addressed together to solve the issue of interoperability. The technologies we use are in a state of flux due to technological change and that will continue to be true for the foreseeable future. These changes will continue to present opportunities to improve productivity that will be difficult to ignore and will likely be incorporated into the systems where they offer credible ROI. We can maximize these
opportunities if we can build systems that are flexible enough to take advantage of the opportunities without major upgrades. The conflicting goal is the need to minimize the cost of the systems over time by squeezing the maximum life out of the investments already made in train control infrastructure. These goals must be addressed in an interoperable solution and may conflict with any general agreement on interoperability.

Interoperability requires an agreement on a minimum set of parameters that will be supported by all participating railroads. Ideally, the minimum set will have room to evolve to support migration to new solutions and methods that will add value over time.

In the ideal system, the locomotive, as the prime mobile element of the train control system, must be capable of supporting a variety of field backbone architectures to allow different solutions to evolve in response to traffic levels and technology changes. The incorporation of a locomotive communications package as outlined above will allow management of the cost issues and a variety of legacy life issues that will occur due to traffic changes and technology advancement over time.

There are also ongoing issues related to interoperable networks and messages as well as security issues that must be addressed to create a true environment for interoperability. The communications package should bridge these issues as they occur.
**Onboard Architecture** — The proposed locomotive package (FIG 3) will include two SDRs, a switching module, dual identity modules, at least one control head and a wireless access point to support the locomotive consist network. This package would be on each data capable locomotive. A tentative physical architecture for the locomotive follows:

**Final Key point:** Transforming the train control environment can help meet future economic and operational challenges at reasonable cost by building into the locomotive and infrastructure architecture a solution that can adapt to change while continuing to support a variety of legacy systems, and allowing the flexibility for train control to be implemented at the location and at the performance level that makes economic sense.
Conclusion

The need for transformation of the entire train control environment is evident from the lack of wide spread implementation after 15 years of effort and multiple versions of the same solution. Peer to Peer communications and an innovative communications package solution has the potential to provide that transformation. The introduction of Peer to Peer communications not only lowers overall costs for the same capabilities but enhances performance and maximizes utilization of the limited spectrum available to the railroads. The further introduction of new communications technologies (i.e., SDR, CMU and Ad-hoc networking) reduces the hardware required and enhances flexibility to incorporate new technologies and techniques while protecting past investment.
## SDR Radio Band Assessment

<table>
<thead>
<tr>
<th>Radio Frequency Band</th>
<th>Train Control</th>
<th>RCL</th>
<th>Peer to Peer控制</th>
<th>Voice</th>
<th>Data</th>
<th>Position</th>
<th>Always Available or Surrogate Operation</th>
<th>SDR Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-50MHz Meteorcomm</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td>CAN</td>
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<tr>
<td>160-162MHz Voice and Data</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td>CAN</td>
<td></td>
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<tr>
<td>220-222MHz PLCT</td>
<td></td>
<td>X</td>
<td>C</td>
<td></td>
<td>X</td>
<td>C</td>
<td>AA</td>
<td></td>
</tr>
<tr>
<td>452-453/457-458MHz EOT/DP</td>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td>X</td>
<td>C</td>
<td>AA</td>
<td></td>
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<td>800MHz/1900MHz Cellular</td>
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<td>X</td>
<td>X</td>
<td>SO</td>
<td>NET</td>
<td></td>
</tr>
<tr>
<td>896-898/935-937MHz ATCS</td>
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<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td>CAN</td>
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<tr>
<td>2400MHz 802.11b</td>
<td></td>
<td>C</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td></td>
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<tr>
<td>1-3GHz Satellite</td>
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<td></td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td>NET</td>
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<tr>
<td>5.8GHz 802.11a/DSRC</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>SO</td>
<td>SO?</td>
<td></td>
</tr>
</tbody>
</table>

### SDR Groups

- Dedicated Radio SDR questionable
- Off the shelf inclusion in SDR
- Candidate for SDR Development
- Networked with SDR

### Capabilities

- Capable: X
- Possible with conflicts: C
- Possible not probable: ?
- AAR Managed Spectrum

Table 1
List of Tables and Figures

Table 1 - “SDR Band Assessment”
(A matrix to evaluate the acceptability of specific radio frequency bands for inclusion into the Software Defined radio package)

Figure 1 - Logical configuration of the locomotive communications package

Figure 2 - Logical configuration of the wireless mobile node
(The diagram depicts the logical networking between three locomotives)

Figure 3 - The physical configuration of the locomotive package

References

1. “Secretary’s PTC Progress Report to the Congress – Outline for Discussion by the Implementation Task Force” (Draft) Section I Page 1

