DEVELOPMENT OF SOFTWARE DEFINED TRAIN RADIO FOR CONVENTIONAL LINES

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ABSTRACT

Safety is our first mission. To insure the safety railway operation, we have to keep in touch between the on board crews and dispatchers.

The train radio is the key technology to tie between them. The radio we have been operated for 20 years, which is used sound technology and not ready for data communication, and the voice distinction is worse than the modern digital radio.

We have some reasons to convert to the digital radio. The first, the voice will be clearer than ever. The second, we can realize the data communication. The third, the bandwidth is narrower than the current system and we can divide from one communication channel to 2 channels.

But before we step forward to digital radio system, we have to make strategy to convert to digital, because the current analog radio stations both fixed and mobiles—are huge numbers and change to digital system gradually. If we can change analog to digital easily, it will be the easiest way to convert to newer system. At that point of view, we noticed that software defined radio can change the radio type by changing the software on the common hardware platform.

In this paper we describe about newly developed train radio using software defined radio (SDR) technology, synchronized between radios via the Ethernet, encryption method for data communication and resolution IP address from train number.

1. CURRENT TRAIN RADIO SYSTEM

The current train radio system for metropolitan area (usually it is called 'type B train radio' among our JR-group.) has some items—the central station, the base stations, the mobile stations and communication network between central station and base stations. The abstract figure is shown on Fig.1 and functions on Fig.2.

Fig.1 Abstract Figure of Current Train Radio Ground System

Fig.2 Functions of Current Train Radio

The current 'type B train radio' contributes for keeping train safer than before. But we found some problems—when we found the place where we could not communicate correctly, we put the additional stations between existence stations. But even if the signal strength is strong enough to be required, the problem is not solved.

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We found two major problems even if the signal level is high enough.

The first problem is distortion of amplifier. As we showed on fig. 1, there are up to 16 amplifiers between the central station and base stations. Even if a single amplifier's distortion level was quite few, integration of distortion of 16 amplifiers are not negligible.

Fig.3 Distortion on the wired network

The second problem is interference between stations. As we showed on Fig.2, every base station is emitting radio wave simultaneously on the same frequency. Mobile station between base stations receives mixed radio waves. These waves contain same information, but phases are different. So waveform of mixed signal is distorted and makes harmonics.

Fig.4 Distortion on the mixed radio waves

The base stations uses below 170Hz single tone signals to control mobile stations and emitting anytime. If the mobile station receives signal from station A and B, Harmonics of tone signals are occurred.

Even if the mobile radio receiver cut below 170Hz, harmonics of tone signals are passed the Low-Pass-Filter. The harmonics of tone signals bothers the voice frequency and it prevents smooth communication between dispatchers and train crews.

Fig.5 Tone signal harmonics spectrum received at mobile station
(Peak=0dB)

2. NEW SDR FOR INTEROPERABILITY AND CONVERTIBLE TO DIGITAL SYSTEM

Since we have huge number of train radio systems, we have to think about interoperability between current 'Type B' train radio and new Software Defined Radio for Train.

We have some point of views to develop the new train radio system.

(1) Interoperability

Current "Type B" train radio's specification is shown as below. New SDR is perfectly compatible with this specification.

Table 1 Comparison of Type-B and New SDR

	Type-B	New SDR (FM software)
Modulation	FM	FM
Modulator/ Demodulator	Hardware	Software Defined
Function	Voice paging 1 to 1 voice communication emergency call	Voice Paging 1 to 1 voice communication emergency call
Control method	tone signaling	tone signaling
Backbone network	Analog 4 wires	I.431a or The Ethernet
Emitting Power	Base station 3W	Base station 3W

(2) Improvement of voice quality

As we showed Fig.3, relay with repeaters will distort the quality of voice.

Even if we are still using analog radio system, we have to improve quality. The point of interface between base station and mobile station is air interface which is radio wave modulation and communication protocol.

We must accord with the air interface when we develop the new SDR system, but we don't have to adopt other than the point of interface.

So we introduced the digital backbone network between stations. If the network will be digitalized, deterioration of voice quality over the repeaters won't occur.

Fig.6 Digitalized repeating vs. analog repeating

But we cannot prevent multi-carrier multi-pass radio interference, because the mobile stations are not changed and perfectly compatible with current system.

If we use the digital radio system, we can eliminate the interference between multi-waves to calculate adaptive equalization over the receiver.

(3) Easy to convert to digital radio system

We have some problems to proceed with analog FM train radio system. We cannot eliminate the interference over the air, because adaptive equalization on the FM radio is more difficult than digital system. Digital systems number of waveforms is limited. So we can expect data from multi-carriers' mixed wave. But FM waveforms are various, so it is very difficult to extraction from mixed wave.

Today, communication over data is as important as over voice. But we cannot communicate data over the 'type-B' train radio.

Digital radio is fit for data and high quality voice communication, but we have some time to change system. We have a lot of trains, base stations all over the Osaka metropolitan area.

So we have to make a strategy to change to digital system. As we describes on the top of this paper, SDR (software defined radio) is key technology of this strategy to make a step forward to the digital world.

3. NEW SOFTWARE DEFINED TRAIN RADIO STRUCTURE

Our train radio common hardware has to fit for both FM and pi/4 shift QPSK.

To ensure this requirement, we have to think about the linearity of final amplifier, frequency conversion and computing power of base processing unit for modulation and de-modulation.

FM transmitter is usually used class-C amplifier and frequency multiply circuit. But they cannot apply for pi/4 shift QPSK modulation. To realize common platform, basically we make AM radio hardware--- we deploy AB-class linear amplifier for power amplification and heterodyne circuit to convert frequency to prevent deviation wider after conversion. The efficiency of final amplifier is lower than before, but this hardware platform is usable for AM/FM/PM.

The abstract hardware block diagram is shown on below.

Fig.7 Block diagram SDR for common hardware

Example for re-modulation calculation method

Receiving signal is amplified, passes through the heterodyne frequency converter and transforms to 7.3MHz intermediate frequency. After that the signal is quantized and sampled at 28.8MHz and processing. The process rule is defined by de-modulation software. Basically, signal is developed to I-Q plain. I(in phase) /Q(quadrature) is defined as below,

$$\begin{aligned} I(n) &= A(n) \cos(\theta(n)) \\ Q(n) &= A(n) \sin(\theta(n)) \end{aligned} \quad (1)$$

for $\theta(n)$: is phase shift value for n-th data.

The modulated wave $f(n)$ is defined

$$f(n) = A(n)\cos(\omega n\Delta t + \theta(n)) \quad (2)$$

$$\begin{aligned} f(n) &= A(t)\cos(\omega n\Delta t)\sin(\theta(n)) + A(t)\sin(\omega n\Delta t)\cos(\theta(n)) \\ &= I(n)\sin(\omega n\Delta t) + Q(n)\cos(\omega n\Delta t) \end{aligned} \quad (3)$$

for ω is carrier frequency(rad), Δt is sampling interval.

If $f(n)$ is known, $I(n)$ and $Q(n)$ can calculate as follows,

$$\begin{aligned} f(n)\cos(\omega n\Delta t) &= I\sin(\omega n\Delta t)\cos(\omega n\Delta t) + Q\cos^2(\omega n\Delta t) \\ &= Q - \underline{Q\sin^2(\omega n\Delta t)} + I\sin(\omega n\Delta t)\cos(\omega n\Delta t) \end{aligned} \quad (4)$$

$$\begin{aligned} f(n)\sin(\omega n\Delta t) &= Q\sin(\omega n\Delta t)\cos(\omega n\Delta t) + I\sin^2(\omega n\Delta t) \\ &= I - \underline{I\cos^2(\omega n\Delta t)} + Q\sin(\omega n\Delta t)\cos(\omega n\Delta t) \end{aligned} \quad (5)$$

Using LPF and eliminate the value underlined. After eliminating with LPF, we can find I and Q value. After finding I and Q calculate as follows;

$$\theta(n) = \tan^{-1}(Q(n)/I(n)) \quad (6)$$

then we finally find the data signal.

4. COMMUNICATION AND SYNCHRONIZATION OVER THE ETHERNET

We need the network between base stations and central station to send the information. Cost of backbone network is the key factor of this radio system. We have to choose most popular, interoperable, international specification-defined, good maintainability and inexpensive network system.

In the other hand, the synchronization is very important for this radio system. If the base stations are not synchronized, mobile station cannot re-modulate from receiving wave.

Emitting radio wave at a time from these stations, we must get synchronize signal from somewhere, typically synchronized wired backbone network, Ground Positioning System or something like that.

We have some limitation to have the synchronized signal--- our every base station is not located at the open air field. Sometimes they are equipped in the tunnels. This is meant we cannot get reference signal from the satellites, always.

The base stations work together with clock signal via backbone network in this case. We are ready for two

network systems. One is a synchronized network I.431.a and the other is synchronizing over the Ethernet.

The Ethernet is most popular network system and this technology covers all over the world. This means it is very easy to maintain the interoperability between network equipments with less cost.

But we have big problem. The Ethernet does not think about to send the synchronization signal. It sends data first-in-first-out basis and collision arbitration method is stored-and-forward on the layer 2 switches.

It means that data transfer time is not sure and depends on the data flow.

Synchronize over the Ethernet is most important issue for this system. There are some techniques to get precise time over the Ethernet as follows.

Table 2 Time synchronization techniques usable over the Ethernet

	<i>RFC1305</i>	<i>IEEE1588-2008</i>
Name	Network Time Protocol (NTP Version 3) Specification, Implementation and Analysis	Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control System
Precision	sub-microsecond range	sub-millisecond range
Use	Network logging Computer time adjusting	Factory Automation
Implementation	Very popular	Not Widely used

NTP is very popular technique to adjust the network equipment, but this radio system requires less than 50 microseconds jitter.

If we can adopt IEEE1588 over the Ethernet, it will be a great solution. But when we were starting this development project, there are very few IEEE1588 protocol stacks and specification was not fixed.

Next, we planned to use NTP to synchronize. But normally, NTP is not suitable and jitter is too big to adapt to this system.

At that time, Nippon Telegraph and Telephone Company was researching ISDN over the Ethernet, and to realize this problem, they thought synchronizing precisely over the Ethernet is most important things to do. To solve it, NTT developed Hardware precision NTP (HwNTP) server.

We were introduced this system and adapt to the train radio.

Fig.8 Synchronization stations over NTP

As we showed Fig. 8, Base stations are trying to access reference clock. But stations are almost synchronized; they are trying to access nearly same timings. It causes packet collision at the Layer 2 switch and precision won't be better. Needless to say, sometimes data transfer between stations and NTP request/response should be collided.

Fig.9 Collide avoiding technique over NTP

HwNTP has some method to avoid this problem. It send NTP packet randomly from the base stations. It makes lower the probability of packet collision than fixed timings. So it is probable to reach to the server without any obstruction sometimes. It seems to be the fastest turn-around between base station and reference clock is no interference among the trip.

If we use the data of shortest turn-around packet, even if the bandwidth of network is nearly full, we can synchronize the base stations properly. We can synchronize the base stations less than 7 microseconds jitter over the gigabit Ethernet on 70% utilization.

5. INTEROPERABLE WITH OTHER RAILWAY OPERATORS

Our railcars sometimes run on the other rail operators. And other operators' cars come to our track. So radio interoperability between us and other JR companies are important issue.

Current radio system--- 'type B' train radio is perfectly compatible between 3 JR companies.

Digital radio system is developed JR-EAST and utilized to Tokyo metropolitan area. We have to think about the interoperability with this system. Our system is compatible with voice communication and uses same modulation, protocols and voice codec.

6. UTILIZATION ON OSAKA-HIGASHI LINE

The Osaka Higashi Line which converted from freight line to passenger and freight line in 2008. It is about 9.2km length from Kyuhoji station to Hanaten station. We are going to extend this line from Hanaten to Shin-Osaka to improve the public transportation in east suburbs Osaka.

The newly converted line equipped our new radio system with 3 base stations. We are operating this radio named 'Digi-B system'. (This means Digital convertible Type-B radio system.)

Fig.10 'Digi-B' Base station at Hanaten station, Osaka-Higashi Line

7. Digital Mode Specification

The digital mode specification is shown on below;

Table 3 Comparison of Digital and Analog mode

	Analog mode of New SDR	Digital mode of New SDR
Modulation	FM	PI/4 shift QPSK
Function	Voice paging 1 to 1 voice communication emergency call	Voice Paging 1 to 1 voice communication emergency call data communication
Bandwidth	8.5kHz tone signaling	5.8kHz
Channels	Voice 1 pair	Voice 2 pairs Control/data 1 pair Data 1 pair
Emitting Power	Base station 3W	Base station 4W

8. FURTHER DEVELOPMENT PLAN

We have some plans to develop and add new features for our new radio system.

(1) Narrowband data communication between trains and central dispatching office

Our new developed radio has data communication mode. Nowadays IP network is de-facto standard for data transfer protocol. We are planning to capsule IP and payload over the radio network and ensure the IP communication.

This has some problems--- IP overhead is not negligible. And if we use TCP/IP, ACK will not come back as smooth as normal backbone. Because transfer rate of data is about 2000-3000bps, ACK timeout may come even if the transferring is perfectly correct.

We will try to establish train radio over IP this year.

(2)Data encryption and key management

We are planning to data encryption with encryption method 'Camellia' developed by NTT and Mitsubishi electric open to public to ensure the data safety and if in case of stolen, mobile stations cannot work anymore.

(3)Resolve between mobile station IP address and train number

If we use IP communication over the train radio, we have to make some scenarios to resolve IP address from train

number. We have various plans to do and we will implement this year.

9. CONCLUSION

We developed new train radio using SDR and network technology and fit for both analog and digital radio. We are examining digital mode at Wakayama Line we will report near future.

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