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Digital Cancelation of Self-Interference for Single-Frequency Full-Duplex Relay Stations via Sampled-Data Control

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Abstract: In this article, we propose sampled-data design of digital filters that cancel the continuous-time effect of coupling waves in a single-frequency full-duplex relay station. In this study, we model a relay station as a continuous-time system while conventional researches treat it as a discrete-time system. For a continuous-time model, we propose digital feedback canceler based on the sampled-data H^∞ control theory to cancel coupling waves taking intersample behavior into account. We also propose robust control against unknown multipath interference. Simulation results are shown to illustrate the effectiveness of the proposed method.

Key Words: wireless communication, coupling wave cancelation, sampled-data control, H^∞ optimization, relay station.

1. Introduction

In wireless communications, relay stations have been used to relay radio signals between radio stations that cannot directly communicate with each other due to the signal attenuation. More recently, relay stations are used to achieve a certain spatial diversity called cooperative diversity to cope with fading channels [1]. On the other hand, it is important to efficiently utilize the scarce bandwidth due to the limitation of frequency resources [2], while conventional relay stations commonly use different wireless resources, such as frequency, time and code, for their reception and transmission of the signals. For this reason, a single-frequency full-duplex relay station, in which signals with the same carrier frequency are received and transmitted simultaneously, is considered as one of key technologies in the fifth generation (5G) mobile communications systems [3]. In order to realize such full-duplex relay stations, *self-interference* caused by coupling waves is the key issue [4].

Fig. 1 illustrates self-interference by coupling waves. In this figure, radio signals with carrier frequency f are transmitted from the base station (denoted by BS). One terminal (denoted by T1) directly receives the signal from the base station, but the other terminal (denoted by T2) is so far from the base station that they cannot communicate directly. Therefore, a relay station (denoted by RS) is attached between them to relay radio signals. Then, radio signals with the same carrier frequency f are transmitted from RS to T2, but also they are fed back to the receiving antenna directly or through reflection objects. As a result, self-interference is caused in the relay station, which may deteriorate the quality of communication and, even worse, may destabilize the closed-loop system.

To tackle with the issue of self-interference cancelation, many methods have been proposed for single-frequency full-duplex systems. Analog cancelation has been proposed in [5],[6], in which analog devices are used for canceling coupling waves. Since coupling wave paths are physically ana-

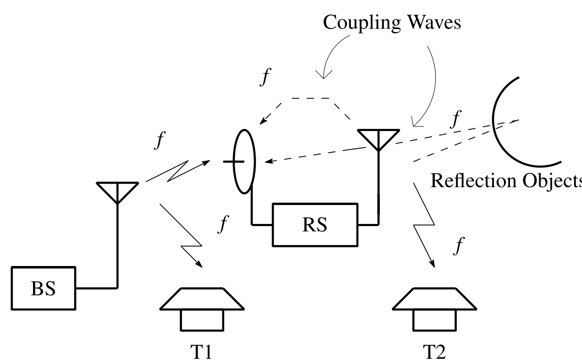

Fig. 1 Self-interference

log systems and there is no quantization problem, this design is theoretically the most ideal except for implementation issues. On the other hand, *digital cancelation* has attracted increasing attention, in which the interference is subtracted in the digital domain by using digital signal processing techniques [7]–[13]. Digital cancelers benefit easy implementation on digital devices in exchange for the response between sampling instants. In addition, spatial domain techniques, called antenna cancelation, has been also proposed in [4],[14], in which they try to reduce the interference by arranging antenna placement. See [4],[8] for details.

For the problem of self-interference, a pre-nulling method [10] and adaptive methods [7],[12] have been proposed to cancel the effect of coupling waves. In these studies, a relay station is modeled by a discrete-time system, and the performance is optimized in the discrete-time domain. However, radio waves are in nature continuous-time signals and hence the performance should be discussed in the continuous-time domain. In other words, one should take account of *intersample behavior* for coupling wave cancelation.

In theory, if the signals are completely band-limited below the Nyquist frequency, then the intersample behavior can be restored from the sampled-data in principle [15], and the discrete-time domain approaches might work well. However, the assumption of perfect band limitedness is hardly satisfied in real signals since

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1. real baseband signals are not fully band-limited,
2. pulse-shaping filters, such as raised-cosine filters, do not act perfectly,
3. and the nonlinearity in electric circuits adds frequency components beyond the Nyquist frequency.

One might think that if the sampling frequency is fast enough, then the assumption is almost satisfied and there is no problem. But this is not true; firstly, the sampling frequency cannot be arbitrarily increased in real systems, and secondly, even though the sampling is quite fast, intersample oscillations may happen in feedback systems [16, Sect. 7].

To solve the problem mentioned above, we propose a new design method for coupling wave cancelation based on the *sampled-data control theory* [16],[17]. We model the transmitted radio signals and coupling waves as continuous-time signals, and optimize the worst case continuous-time error due to coupling waves by a *digital* canceler. This is formulated as a sampled-data H^∞ optimal control problem, which can be solved via the fast-sampling fast-hold (FSFH) method [18],[19]. We also propose robust feedback cancelers that can take account of uncertainties in coupling wave path characteristic such as unknown multipath interference due to, for example, large structures that reflect radio waves, or the change of weather conditions [20]. Design examples are shown to illustrate the proposed methods.

The present manuscript expands on our recent conference contributions [21],[22] by incorporating robust feedback control into the formulation.

The remainder of this article is organized as follows. In Section 2, we derive a mathematical model of a relay station considered in this study. In Section 3, we propose sampled-data H^∞ control for cancelation of self-interference. Here we also discuss robust control against uncertainty in the delay time. In Section 4, simulation results are shown to illustrate the effectiveness of the proposed method. In Section 5, we offer concluding remarks.

Notation

Throughout this article, we use the following notation. We denote by L^2 the Lebesgue space consisting of all square integrable real functions on $[0,\infty)$ endowed with L^2 norm $\|\cdot\|_2$. The symbol t denotes the argument of time, s the argument of Laplace transform and z the argument of Z transform. These symbols are used to indicate whether a signal or a system is of continuous-time or discrete-time. The operator e^{-Ls} with nonnegative real number L denotes the continuous-time delay operator with delay time L. For a matrix A, $\overline{\sigma}(A)$ denotes the maximum singular value of A.

2. Relay Station Model

In this section, we provide a mathematical model of a relay station with self-interference phenomenon.

Fig. 2 depicts a single-frequency full-duplex relay station implemented with a digital canceler [6]. A radio wave with carrier frequency f from a base station is accepted at the receiving antenna and amplified by the low noise amplifier (LNA). Then, the received signal is demodulated to a baseband signal by the demodulator, and converted to a digital signal by the analog-to-digital converter (ADC). The obtained digital signal is then

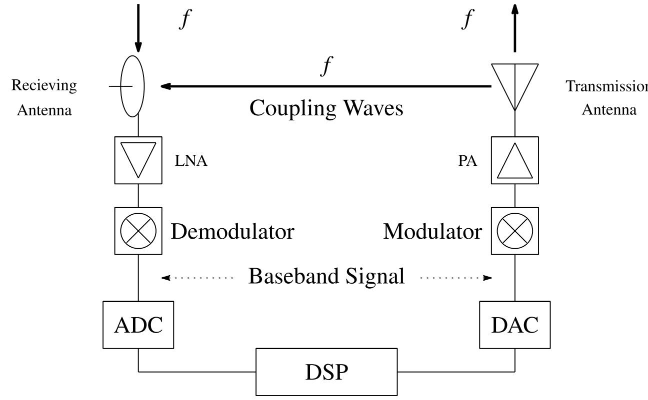

Fig. 2 Relay Station

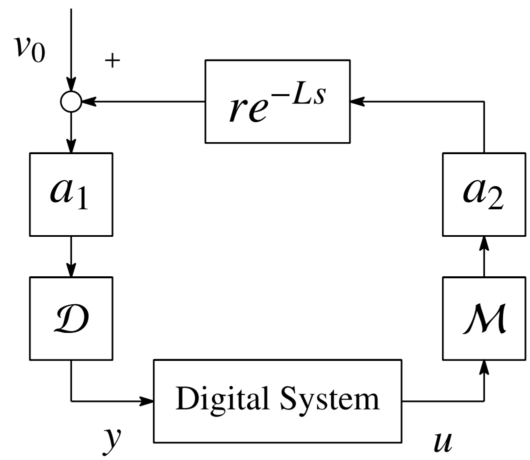

Fig. 3 Simple Block Diagram of Relay Station

processed by the digital signal processor (DSP) into another digital signal, which is converted to an analog signal by the digital-to-analog converter (DAC). Finally, the analog signal is modulated to a radio wave with carrier frequency f, amplified by the power amplifier (PA) and transmitted by the transmission antenna. A problem here is that the transmitted signal will again reach the receiving antenna. This is called coupling wave and causes self-interference, which deteriorates the communication quality.

Fig. 3 shows a simplified block diagram of the relay station. In Fig. 2, we model LNA and PA in Fig. 2 as static gains, a_1 and a_2, respectively. The modulator is denoted by $\mathcal{M}$ and the demodulator by $\mathcal{D}$. We assume that the coupling wave channel is a flat fading channel, that is, all frequency components of a signal through this channel experience the same magnitude fading. Then the channel can be treated as an all-pass system. In this study, we adopt a delay system, re^{-Ls}, as a channel model, where $r > 0$ is the attenuation rate and $L > 0$ is a delay time. The block named "Digital System" includes ADC, DSP and DAC in Fig. 2.

In this article, we consider the quadrature amplitude modulation (QAM), which is used widely in digital communication systems, as a modulation method. QAM transforms a transmission signal into two orthogonal carrier waves, that is a sine wave and a cosine wave. We assume the transmission signal $u(t)$ is given by

$$u(t) := \sum_k g(t-kh) \begin{bmatrix} u_k^I \\ u_k^Q \end{bmatrix}. \quad (1)$$

In this expression, $g(t)$ is a general pulse-shaping function, h is the sampling period, and u_k^I, u_k^Q denote respectively the in-phase and the quadrature components of a transmission symbol. We assume that the support of the Fourier transform $G(j\omega)$ of $g(t)$ is finite and the bandwidth is much less than $4\pi f$. In other words, there exists a frequency f_g $(0 < f_g \ll f)$ such that $|G(j\omega)| = 0$ for any $\omega \notin (-2\pi f_g, 2\pi f_g)$. Then the modulated signal $\tilde{u}(t)$ can be written as [23, Chap. 2]

$$\begin{aligned}\tilde{u}(t) &= \mathcal{M}u(t) \\ &= \sum_k g(t-kh)(u_k^I \cos 2\pi f t - u_k^Q \sin 2\pi f t). \quad (2)\end{aligned}$$

On the other hand, the demodulation operator $\mathcal{D}$ is a linear operator satisfying $\mathcal{D}\mathcal{M} = 1$ [23]. Fig. 4 shows the block diagram of $\mathcal{D}$. In this block diagram, $H_{\mathrm{id}}(j\omega)$ is the ideal low-pass filter with cut-off frequency f_c satisfying

$$H_{\mathrm{id}}(j\omega) = \begin{cases} 1, & \text{if } \omega < 2\pi f_c, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

The cut-off frequency is chosen to satisfy $f_g \ll f_c \ll f$. By the linearity of $\mathcal{D}$, we obtain an equivalent block diagram shown in Fig. 5 to Fig. 3. Here

$$\begin{aligned}\tilde{u}(t-L) = &\sum_k g(t-L-kh)\Big\{(u_k^I \cos(2\pi f L) \\ &+ u_k^Q \sin(2\pi f L)) \cos(2\pi f t) \\ &+ (u_k^I \sin(2\pi f L) - u_k^Q \cos(2\pi f L)) \sin(2\pi f t)\Big\}. \quad (4)\end{aligned}$$

Thus, we have

$$\begin{aligned}&\cos(2\pi f t) \cdot \tilde{u}(t-L) \\ &= \frac{1}{2} \sum_k g(t-L-kh)\Big\{u_k^I \cos(2\pi f L) + u_k^Q \sin(2\pi f L) \\ &+ (u_k^I \cos(2\pi f L) + u_k^Q \sin(2\pi f L)) \cos(4\pi f t) \\ &+ (u_k^I \sin(2\pi f L) - u_k^Q \cos(2\pi f L)) \sin(4\pi f t)\Big\}. \quad (5)\end{aligned}$$

From this, we have

$$\begin{aligned}&2H_{\mathrm{id}}[\cos(2\pi f t) \cdot \tilde{u}(t-L)] \\ &= \sum_k g(t-L-kh)\{u_k^I \cos(2\pi f L) + u_k^Q \sin(2\pi f L)\}. \quad (6)\end{aligned}$$

In the same way, we have

$$\begin{aligned}&2H_{\mathrm{id}}[-\sin(2\pi f t) \cdot \tilde{u}(t-L)] \\ &= \sum_k g(t-L-kh)\{-u_k^I \sin(2\pi f L) + u_k^Q \cos(2\pi f L)\}. (7)\end{aligned}$$

Finally, we have the following relation:

$$\begin{aligned}u_L(t) &= \mathcal{D}(a_1 r a_2 \tilde{u}(t-L)) \\ &= \alpha A_L u(t-L), \quad (8)\end{aligned}$$

where $\alpha := a_1 a_2 r$ and

$$A_L := \begin{bmatrix} \cos(2\pi f L) & \sin(2\pi f L) \\ -\sin(2\pi f L) & \cos(2\pi f L) \end{bmatrix}. \quad (9)$$

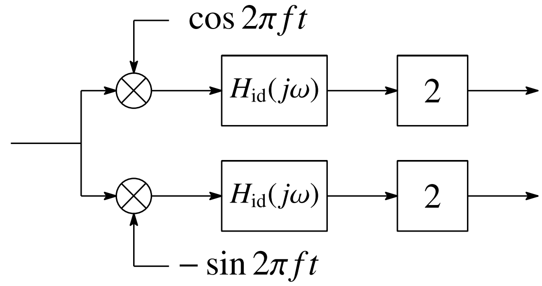

Fig. 4 Structure of a demodulator

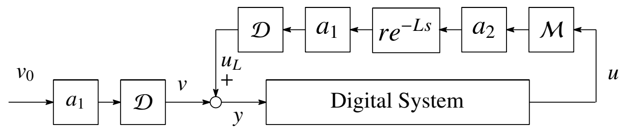

Fig. 5 Equivalent Block Diagram of Relay Station

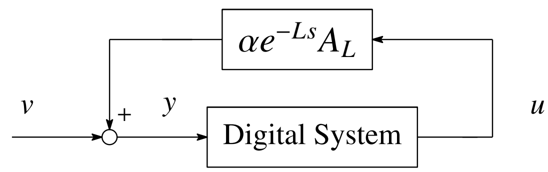

Fig. 6 Relay Station Model

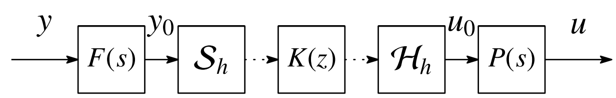

Fig. 7 Digital System

Finally we obtain a relay station model depicted in Fig. 6. By this figure, we can see that the relay station with self-interference is a *feedback* system. In practice, the gain of PA in Fig. 2 is very high (e.g., $a_2 = 1000$) and the loop gain becomes much larger than 1, and hence we should discuss the *stability* as well as self-interference cancelation. To achieve these requirements, we design the digital controller in the digital system, which is precisely shown in Fig. 7.

In Fig. 7, ADC in Fig. 2 is modeled by an anti-aliasing analog filter $F(s)$ with an ideal sampler $\mathcal{S}_h$ with sampling period $h > 0$, defined by

$$\begin{aligned}\mathcal{S}_h : \{y_0(t)\} \mapsto \{y_d[n]\} : y_d[n] = y_0(nh), \\ n = 0, 1, 2, \ldots.\end{aligned} \quad (10)$$

For the DSP block in Fig. 2, we assume a digital filter denoted by $K(z)$, which we design for self-interference cancelation. DAC in Fig. 2 is modeled by a zero-order hold, $\mathcal{H}_h$, defined by

$$\begin{aligned}\mathcal{H}_h : \{u_d[n]\} \mapsto \{u_0(t)\} : u_0(t) = u_d[n], \\ t \in [nh, (n+1)h), n = 0, 1, 2, \ldots,\end{aligned} \quad (11)$$

and a post analog low-pass filter denoted by $P(s)$. We assume that $F(s)$ and $P(s)$ are proper, stable and real-rational transfer function matrices. Note that a strictly proper function is normally used for $F(s)$ and it is included in the assumption.

3. Feedback Control

Fig. 8 shows the block diagram of the feedback control system of the relay station. For this system, we find the digital

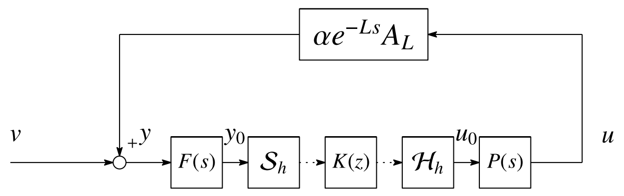

Fig. 8 Feedback Canceler

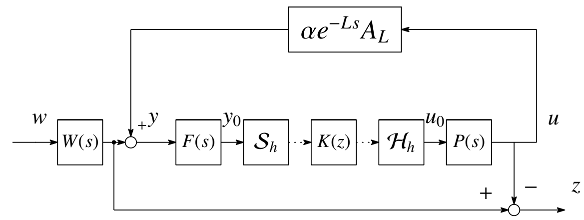

Fig. 9 Block Diagram for Feedback Canceler Design

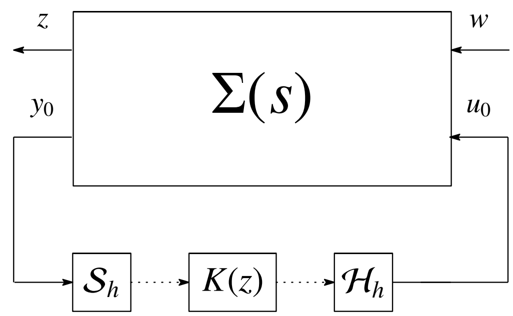

Fig. 10 LFT $T_{zw} = \mathcal{F}(\Sigma, \mathcal{H}_h K \mathcal{S}_h)$

controller, $K(z)$, that stabilizes the feedback system and also minimize the effect of self-interference, $z := v - u$, for any v. To obtain a reasonable solution, we restrict the input continuous-time signal v to the following set

$$WL^2 := \{v = Ww : w \in L^2, \|w\|_2 = 1\}, \tag{12}$$

where W is a continuous-time LTI system with real-rational, stable, and strictly proper transfer function $W(s)$. Under this assumption, we first solve a *nominal* control problem where all system parameters are previously known. Then we propose a *robust* controller design against uncertainty in the coupling wave paths.

3.1 Nominal Controller Design

Here we consider the nominal controller design problem formulated as follows:

Problem 1 Find the digital controller (canceler) $K(z)$ that stabilizes the feedback system in Fig. 8 and uniformly minimizes the L^2 norm of the error $z = v - u$ for any $v \in WL^2$.

This problem is reducible to a standard sampled-data H^∞ control problem [16],[17]. To see this, let us consider the block diagram shown in Fig. 9. Let T_{zw} be the system from w to z. Then we have

$$z = v - u = T_{zw}w \tag{13}$$

and hence uniformly minimizing $\|z\|_2$ for any $v \in WL^2$ is equivalent to minimizing the H^∞ norm of T_{zw},

$$\|T_{zw}\|_\infty = \sup_{w \in L^2,\ \|w\|_2 = 1} \|T_{zw}w\|_2. \tag{14}$$

Let $\Sigma(s)$ be a generalized plant given by

$$\Sigma(s) = \begin{bmatrix} W(s) & -P(s) \\ F(s)W(s) & \alpha e^{-Ls}A_L F(s)P(s) \end{bmatrix}. \tag{15}$$

By using this, we have

$$T_{zw}(s) = \mathcal{F}(\Sigma(s), \mathcal{H}_h K(z) \mathcal{S}_h), \tag{16}$$

where $\mathcal{F}$ denotes the linear-fractional transformation (LFT) [17]. Fig. 10 shows the block diagram of this LFT. Then our problem is to find a digital controller $K(z)$ that minimizes $\|T_{zw}\|_\infty$. This is a standard sampled-data H^∞ control problem, and can be efficiently solved via FSFH approximation [18],[19],[24].

Note that if there exists a controller $K(z)$ that minimizes $\|T_{zw}\|_\infty$, then the feedback system is stable and the effect of self-interference $z = v - u$ is bounded by the H^∞ norm. We summarize this as a proposition.

Proposition 1 Assume $\|T_{zw}\|_\infty \leq \gamma$ with $\gamma > 0$. Then the feedback system shown in Fig. 8 is stable, and for any $v \in WL^2$ we have $\|v - u\|_2 \leq \gamma$.

Proof First, if the feedback system is unstable, then the H^∞ norm becomes unbounded. Next, for $v \in WL^2$ there exists $w \in L^2$ such that $v = Ww$ and $\|w\|_2 = 1$. Then, inequality $\|T_{zw}\|_\infty \leq \gamma$ gives

$$\|v - u\|_2 = \|T_{zw}w\|_2 \leq \|T_{zw}\|_\infty \|w\|_2 \leq \gamma. \tag{17}$$

□

3.2 Robust Controller Design against Multipath Interference

In practice, the characteristic of the coupling wave channel changes due to, for example, large structures that reflect radio waves. In this situation, it is difficult to predict the coupling wave paths beforehand, and hence there must be uncertainties in the paths. Under this uncertainty, the nominal controller may lead to deterioration of cancelation performance, and even worse, it may make the feedback system unstable. To solve this problem, we propose *robust* controller design against the uncertainty.

Let us assume the characteristic of the coupling wave paths in Fig. 6 is perturbed as

$$re^{-Ls} \mapsto re^{-Ls} + \sum_{i=1}^{M} r_i e^{-L_i s}, \tag{18}$$

where r_i and L_i are the attenuation ratio and the delay time of the i-th path, respectively. Note that M represents the number of additional paths. Since the additional paths are detour paths, we assume

$$L_i > L, \quad i = 1, 2, \ldots, M. \tag{19}$$

Then the characteristic of the feedback path in Fig. 8 is perturbed as

$$\alpha e^{-Ls}A_L \mapsto \alpha e^{-Ls}A_L + \sum_{i=1}^{M} \alpha_i e^{-L_i s} A_{L_i} \tag{20}$$

where $\alpha_i := a_1 a_2 r_i$. Define the error transfer function matrix $E(s)$ as

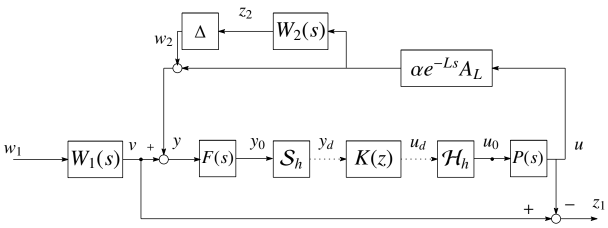

Fig. 11 Relay Station Model with Perturbation

$$E(s) := \sum_{i=1}^{M} \frac{\alpha_i}{\alpha} e^{-(L_i-L)s} A_{L_i-L}. \tag{21}$$

Since A_L is a rotation matrix on $\mathbf{R}^2$ and the angle is $2\pi fL$ clockwise, we have

$$\begin{aligned}
&\alpha e^{-Ls}A_L + \sum_{i=1}^{M} \alpha_i e^{-L_i s} A_{L_i} \\
&= \alpha e^{-Ls} A_L \left(I + \sum_{i=1}^{M} \frac{\alpha_i}{\alpha} e^{-(L_i-L)s} A_L^{-1} A_{L_i} \right) \\
&= \alpha e^{-Ls} A_L \left(I + E(s) \right).
\end{aligned} \tag{22}$$

Take a frequency weighting function matrix $W_2(s)$ that is real rational and satisfies

$$\overline{\sigma}(E(j\omega)) < \overline{\sigma}(W_2(j\omega)), \tag{23}$$

for all $\omega \in \mathbf{R}$. Since A_{L_i-L} is an orthogonal matrix, the equation (21) gives

$$\overline{\sigma}(E(j\omega)) \le \sum_{i=1}^{M} \frac{\alpha_i}{\alpha} \overline{\sigma}\left(e^{-j(L_i-L)\omega} A_{L_i-L} \right) \le \sum_{i=1}^{M} \frac{r_i}{r}. \tag{24}$$

Then the uncertainty in the coupling wave paths can be modeled as multiplicative perturbation, that is, for any $M > 0$, $r_i \ge 0$, $L_i > L$ ($i = 1, \ldots, M$), we have

$$\begin{aligned}
&\alpha e^{-Ls}A_L + \sum_{i=1}^{M} \alpha_i e^{-L_i s} A_{L_i} \\
&\in \{\alpha e^{-Ls} A_L (1 + \Delta(s) W_2(s)) : \|\Delta\|_\infty < 1\}.
\end{aligned} \tag{25}$$

From the inequality (24), we can take

$$W_2(s) = \left(\sum_{i=1}^{M} \frac{r_i}{r} + \varepsilon \right) I \tag{26}$$

where ε is an appropriately small and positive number.

Based on the formulation of the uncertainty, we consider the block diagram shown in Fig. 11, where $W_1(s)$ plays the same role as $W(s)$ in the nominal controller design. Let $T_{z_1 w_1}$ be the system from w_1 to z_1 and $T_{z_2 w_2}$ be the system from w_2 to z_2. If $\|T_{z_1 w_1}\|_\infty$ is finite and $\|T_{z_2 w_2}\|_\infty \le 1$, then the feedback system is robustly stable, that is, the feedback system is internally stable for all Δ satisfying $\|\Delta\|_\infty < 1$ from the small gain theorem for sampled-data control systems [25].

Now we formulate the robust controller design problem as follows:

Problem 2 Find the digital controller (canceler) $K(z)$ that minimizes $\|T_{z_1 w_1}\|_\infty$ subject to $\|T_{z_2 w_2}\|_\infty \le 1$.

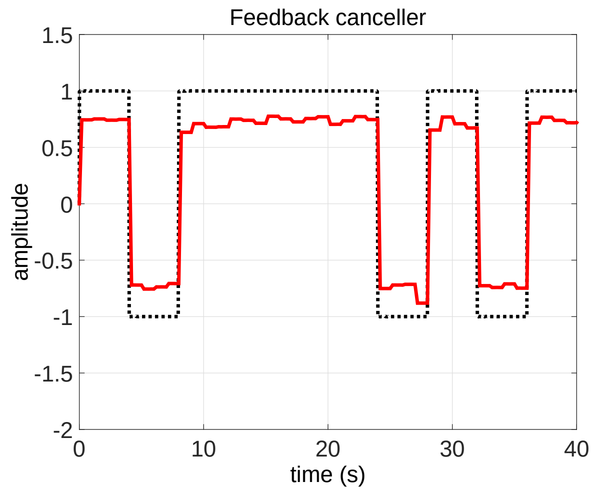

Fig. 12 Feedback Cancelation: input signal (dash-dot line), reconstructed signal u by feedback canceler (solid line)

To solve this problem, we adopt the finite dimensional Q-parametrization where we limit feasible controllers [26]. Then, the constraints are represented by linear matrix inequalities (LMI's) and the problem can be efficiently solved via numerical optimization software such as `SDPT3` or `SeDuMi` on `MATLAB` [27],[28]. For more details, see [26].

4. Design Examples

In this section, we show simulation results to illustrate the effectiveness of the proposed methods.

We assume that the sampling period h is normalized to 1, the carrier frequency f is 10000 Hz, the attenuation rate of the coupling wave channel $r = 0.2$, and the time delay $L = 1$. Note that sampling frequency is 1 Hz, which is much smaller than the carrier frequency. Note also that the time delay is equal to the sampling period h. We assume the low noise amplifier $a_1 = 1$. An anti-alias analog filter is not employed in this examples, namely we assume $F(s) = I$. The post filter $P(s)$ is modeled by

$$P(s) = \frac{1}{0.001s + 1} I. \tag{27}$$

We also assume the transmission gain to be

$$a_2 = 1000, \tag{28}$$

that is, 60 dB. The frequency characteristic $W(s)$ is modeled by

$$W(s) = \frac{1}{2s + 1} I. \tag{29}$$

With these parameters, we compute the H^∞-optimal nominal controller $K(z)$ by FSFH with discretization number $N = 16$.

With this controller, we simulate coupling wave cancelation with a random rectangular wave input with period 4 s filtered by the low-pass filter $P(s)$. Note that this signal contains frequency components beyond the Nyquist frequency, $\pi/h = \pi$ [rad/sec], although the frequency of the wave, $\pi/8h = \pi/8$ [rad/sec] is much lower than π. Fig.12 shows the reconstructed signal u in the feedback system (see Fig. 8). The feedback system is guaranteed to be stable and the canceler achieves small reconstruction errors as shown in Fig. 13.

Next, let us consider uncertainty in the coupling wave paths. If the characteristic of the coupling wave paths changes, then

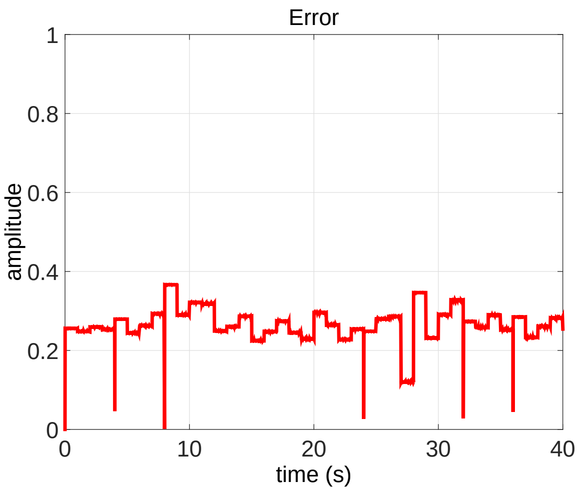

Fig. 13 Coupling wave effect $|v(t) - u(t)|$ by feedback canceler shown in Fig. 8

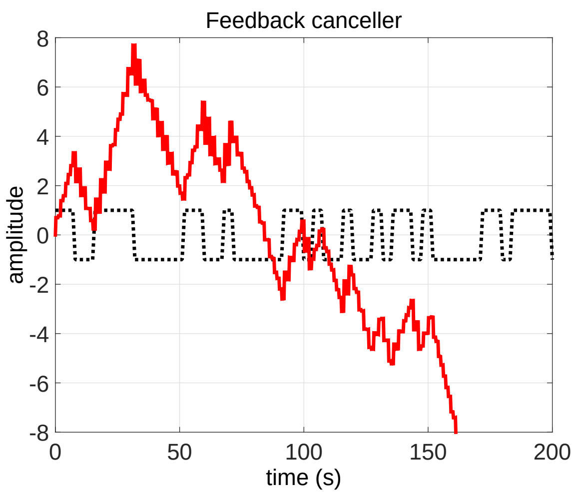

Fig. 14 Feedback Cancelation: input signal (dash-dot line) and reconstructed signal (solid line) with the perturbation

the nominal controller may not work well. To see this, let us design the nominal controller with

$$a_2 = 100, \tag{30}$$

that is, 40 dB, and the other parameters are the same as above. Then perturbing the nominal coupling wave path to be

$$re^{-Ls} + r_1 e^{-L_1 s} \tag{31}$$

where $r_1 = 0.07r, L_1 = 1.1L$. It results in instability as shown in Fig. 14.

To overcome this, we use the robust controller proposed in subsection 3.2, $M = 1$, $r_1 = 0.1r$ with $W_1(s) = W(s)$ given in (29) and $W_2(s)$ as in (26). The dimension of Q-parametrization is 8 with the FSFH number $N = 4$. Fig. 15 shows the reconstructed signal, by which we can observe the robust controller works well.

5. Conclusions

In this paper, we have proposed feedback controller design for self-interference cancelation in single-frequency full-duplex relay stations based on the sampled-data H^∞ control theory. In particular, we proposed robust controller design against the unknown additive multipath. Simulation results have been shown

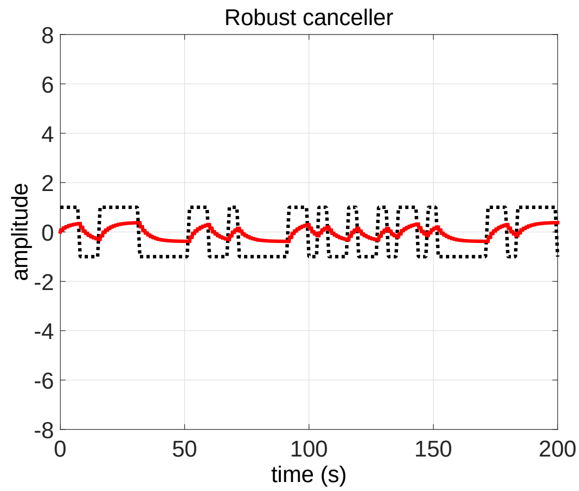

Fig. 15 Robust Cancelation: input signal (dash-dot line) and reconstructed signal (solid line) with the perturbation.

to illustrates the effectiveness of the proposed cancelers in view of stability and robust stability. Future work may include FIR (Finite Impulse Response) filter design and adaptive FIR filtering as discussed in [29],[30].

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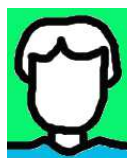
Kazunori Hayashi



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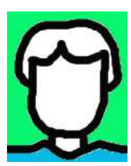

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