Sampled-Data $H^\infty$ Design of Coupling Wave Cancelers in Single-Frequency Full-Duplex Relay Stations

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Abstract: In this article, we propose sampled-data $H^\infty$ 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 feedforward and feedback cancelers based on the sampled-data control theory to cancel coupling waves taking intersample behavior into account. Simulation results are shown to illustrate the effectiveness of the proposed method.

Keywords: wireless communication, coupling wave cancelation, sampled-data control, $H^\infty$ optimization.

1. INTRODUCTION

In wireless communications, relay stations are used to relay radio signals between radio stations that cannot directly communicate with each other due to the signal attenuation. On the other hand, it is important to efficiently utilize the scarce bandwidth due to the limitation of frequency resources [2, Chap. 1]. For this purpose, single-frequency network is often preferable in which signals with the same carrier frequency are transmitted through communication networks. Then, a problem of self-interference caused by coupling waves arises in a full-duplex relay station in a single-frequency network [3].

Fig. 1 illustrates self-interference by coupling waves. In this picture, radio signals with carrier frequency $f_1$ 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 carrier frequency $f_1$ from the transmission antenna of the relay station 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 system.

For the problem of self-interference, adaptive methods have been proposed to cancel the effect of coupling waves: a least mean square (LMS) adaptive filters [9], and adaptive array antennas [8]. 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 [11], and the discrete-time domain approaches might work well. However, the assumption of perfect band-limitedness is hardly satisfied in real signals; real baseband signals are not fully band-limited (otherwise they must be non-causal [12, Chap. 1]), pulse-shaping filters, such as raised-cosine filters, do not act perfectly, and the non-linearity in electric circuits adds frequency components beyond the Nyquist frequency. One might think that if the sampling frequency is fast enough, 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 [13, 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 [1, 13]. 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 $H^\infty$ optimal control problem, which is solved via the fast-sampling fast-hold (FSFH) method [4, 14]. In this study, we consider two types of digital canceler: feedforward
and feedback cancelers. For a feedforward canceler\(^1\), we cancel self-interference by a discrete-time (virtual) model of the coupling wave path that is optimized via sampled data \(H^\infty\) optimization [6, 15]. For a feedback canceler, we place a digital controller in the feedback loop for stabilizing the feedback system as well as canceling the self-interference. This is formulated as a standard sampled-data \(H^\infty\) control problem except for the time delay in the feedback loop, which can be solved via FSFH as well. Design examples are shown to illustrate the proposed methods.

The reminder of this article is organized as follows. In Section 2, we formulate a design problem of feedforward cancelers. In Section 3, we formulate a feedback canceler design problem as a sampled-data \(H^\infty\) optimal control problem, which can be solved via FSFH approximation described in Section 4. In Section 5, simulation results are shown to illustrate the effectiveness of the proposed method. In Section 6, 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 \(\| \cdot \|_{L^2}\), and \(\ell^2\) the space consisting of all square summable sequences, with \(\ell^2\) norm \(\| \cdot \|_{\ell^2}\). 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 continuous-time delay operator with delay time \(L\). A continuous-time (or discrete-time) system \(G\) with transfer function \(C(sI - A)^{-1}B + D\) (or \(C(zI - A)^{-1}B + D\)) is denoted by

\[
G = \begin{bmatrix} A & B \\ C & D \end{bmatrix}.
\]

**2. FEEDFORWARD CANCELERS**

In this section, we formulate the design problem of feedforward cancelers.

Fig. 2 shows the block diagram of a relay station using an amplify and forward relaying protocol with a coupling wave path and a digital feedforward canceler. In Fig. 2, continuous-time signals are represented in solid lines and discrete-time signals in dotted lines. We model the relay station by a continuous-time linear time-invariant (LTI) system with transfer function \(G(s)\). The characteristic of the coupling wave path is also modeled by a continuous-time LTI system denoted by \(P(s)\) with time delay \(e^{-Ls}\) where \(L\) is a fixed nonnegative real number (i.e. \(L\) is a fixed delay time). Note that \(P(s)\) will be time-varying in general due to the Doppler shift caused by the movement of reflection objects, however, the assumption of the LTI system is valid if the movement is slow or the signal components coming from the moving objects are not dominant. The digital canceler consists of three operators: ideal sampler \(S_h\) with sampling period \(h > 0\), digital filter \(K(z)\), and zero-order hold \(H_h\) with the same sampling period \(h\). The ideal sampler is defined by

\[
S_h : \{y(t)\} \rightarrow \{y_d[n]\} : y_d[n] = y(nh), \quad n = 0, 1, 2, \ldots,
\]

and the zero-order hold is defined by

\[
H_h : \{u_d[n]\} \rightarrow \{u(t)\} : u(t) = \sum_{n=0}^{\infty} u_d[n], \quad t \in [nh, (n+1)h), \quad n = 0, 1, 2, \ldots.
\]

From Fig. 2, we have

\[
y = v + (e^{-Ls}PG - H_hK_S)y.
\]

(1)

To model the characteristic of the input signal \(y\), we introduce a subset \(FL^2 \subset L^2\) defined by

\[
FL^2 := \{y = Fw : w \in L^2, \|w\|_{L^2} = 1\},
\]

where \(F\) is a continuous-time LTI system with real-rational, stable, and strictly proper transfer function \(F(s)\). The transfer function is a frequency domain weighting function that gives the frequency characteristic of \(y\). Note that this signal model allows non band-limited signals such as rectangular waves. For any \(y \in FL^2\), we try to uniformly minimize the error

\[
e := (e^{-Ls}PG - H_hK_S)y = (e^{-Ls}PG - H_hK_S)Fw.
\]

In other words, we minimize the \(H^\infty\) norm of the error system (see Fig. 3)

\[
E(K) := (e^{-Ls}PG - H_hK_S)F,
\]

that is,

\[
\inf_{K_{\text{stable}}} \|E(K)\|_\infty = \inf_{K_{\text{stable}}} \sup_{w \in L^2, \|w\|_{L^2} = 1} \|E(K)w\|_{L^2}.
\]

The optimal discrete-time filter \(K(z)\) can be obtained

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\(^1\) A feedforward canceler was first reported in [10].

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\(^2\) Although the assumption that \(y \in FL^2\) is artificial, we here consider a much wider class of signals than the band-limited signal class assumed in Shannon’s theorem.
via FSFH discretization [4, 14]. For details of the design procedure, see [6].

If we use the $H^\infty$ optimal filter $K(z)$ for the relay station that achieves sufficiently small $\|\mathcal{E}(K)\|_\infty$, the effect of the coupling wave, $y - v$, is sufficiently reduced. In fact, we have the following theorem:

**Theorem 1:** Assume $\|\mathcal{E}(K)\|_\infty \leq \gamma$ with $\gamma > 0$.
Then for any $y \in FL^2$ we have $\|y - v\|_{L^2} \leq \gamma$.

**Proof:** For any $y \in FL^2$, there exists $w \in L^2$ such that $y = Fw$ with $\|w\|_{L^2} = 1$. This and equation (1) give

$$\|y - v\|_{L^2} = \|(e^{-Ls}PG - \mathcal{H}_hKS_h)\|_{L^2}$$

$$= \|(e^{-Ls}PG - \mathcal{H}_hKS_h)Fw\|_{L^2}$$

$$\leq \|\mathcal{E}(K)\|_\infty$$

$$\leq \gamma.$$

This theorem motivates the proposed $H^\infty$ optimal design for cancelation of coupling waves.

3. FEEDBACK CANCELERS

The feedforward canceler shown in Fig. 2 works well when the gain of $G(s)$ is low. If the gain of $G(s)$ is very high, the self-interference feedback loop including the coupling wave path may become unstable. Since the feedforward canceler design does not take the stability into account, it cannot generally stabilize the feedback loop. Therefore, we here consider a feedback canceler to stabilize the feedback loop as well as reducing the effect of self-interference. Fig. 4 shows the block diagram of a relay station attached with a digital feedback canceler $\mathcal{H}_h, K(z)S_h$. The difference between this and the feedforward canceler in Fig. 2 is that the canceler is placed in the feedback loop.

Our problem here is to design the digital controller, $K(z)$, that stabilizes the feedback loop and minimize the effect of self-interference, $z := v - u$, for any $v$. We restrict the input continuous-time signal $v$ to the following set:

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

where $W$ is a continuous-time LTI system with real-rational, stable, and strictly proper transfer function $W(s)$. The design problem is formulated as follows:

**Problem 1:** Design digital controller (canceler) $K(z)$ that stabilizes the self-interference feedback loop and uniformly minimizes the $L^2$ norm of the error $z = v - u$ for any $v \in W L^2$.

This problem is reducible to a standard sampled-data $H^\infty$ control problem [1, 13]. To see this, let us consider the block diagram shown in Fig. 5. Let $T_{zw}$ be the system from $w$ to $z$. Then we have

$$z = v - u = T_{zw}w$$

and hence uniformly minimizing $\|z\|_{L^2}$ for any $v \in WL^2$ is equivalent to minimizing the $H^\infty$ norm of $T_{zw}$.

$$\|T_{zw}\|_\infty = \sup_{w \in WL^2, \|w\|_{L^2} = 1} \|T_{zw}w\|_{L^2}.$$ (2)

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

$$\Sigma(s) = \begin{bmatrix} W(s) & -1 \\ W(s) & e^{-Ls}P(s)G(s) \end{bmatrix}.$$ (3)

By using this, we have

$$T_{zw}(s) = \mathcal{F}(\Sigma(s), \mathcal{H}_hK(z)S_h),$$

where $\mathcal{F}$ denotes the linear-fractional transformation (LFT) [1]. Fig. 6 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 $H^\infty$ control problem, and can be efficiently solved via FSFH approximation. We discuss this in the next section.

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 $H^\infty$ norm. We summarize this as a theorem.
Theorem 2: Assume \(\|T_{zw}\|_\infty \leq \gamma\) with \(\gamma > 0\). Then the feedback system shown in Fig. 4 is stable, and for any \(v \in W L^2\) we have \(\|v - u\|_{L^2} \leq \gamma\).

Proof: First, if the feedback system is unstable, then the \(H^\infty\) norm becomes unbounded. Next, for \(v \in W L^2\) there exists \(w \in L^2\) such that \(v = Ww\) and \(\|w\|_{L^2} = 1\). Then, inequality \(\|T_{zw}\|_\infty \leq \gamma\) gives
\[
\|v - u\|_{L^2} = \|T_{zw}w\|_{L^2} \leq \|T_{zw}\|_\infty \|w\|_{L^2} \leq \gamma.
\]

4. FAST-SAMPLE FAST-HOLD APPROXIMATION

In this section, we review the method of FSFH approximation for sampled-data \(H^\infty\) optimal controller design. The idea of FSFH is approximating a continuous-time \(L^2\) signal by a piecewise constant signal, which is generated by a fast hold \(H_{h/N}\) where \(N\) is an integer greater than 2, and evaluating the \(L^\infty\) norm of an \(L^2\) signal on the sampling points generated by \(S_{h/N}\). We call \(S_{h/N}\) and \(H_{h/N}\) a fast sampler and a fast hold, respectively. That is, we connect the fast sampler and hold to the continuous-time signals, \(z\) and \(w\), in Fig. 6 respectively, to make a generalized plant with discrete-time input/output as shown in Fig. 7.

Roughly speaking, if we take \(N \rightarrow \infty\), then the frequency response of the FSFH approximation \(S_{h/N}T_{zw}H_{h/N}\) uniformly approaches that of sampled-data system \(T_{zw}\), see [14] for details. Since the \(H^\infty\) norm defined in (2) is equivalent to the maximum gain of the frequency response gain of the sampled-data system \(T_{zw}\) (defined via lifting) [1, Chap. 13], we can obtain an approximated solution of our \(H^\infty\) optimal control problem if we take a sufficiently large \(N\).

The FSFH approximation of sampled-data \(T_{zw}\) in Fig. 7 contains two sampling periods, \(h\) and \(h/N\), and the whole system is periodically time-varying. By using discrete-time lifting defined below, the system can be equivalently converted to a finite-dimensional discrete-time LTI system. The discrete-time lifting is defined by
\[
\mathbf{L}_N : \{x[0], x[1], \ldots\} \\
\mapsto \begin{bmatrix} x[0] \\ \vdots \\ x[N-1] \end{bmatrix}, \begin{bmatrix} x[N] \\ \vdots \\ x[2N-1] \end{bmatrix}, \ldots
\]

and its inverse by
\[
\mathbf{L}_N^{-1} : \begin{bmatrix} x_1[0] \\ \vdots \\ x_N[0] \\ \vdots \\ x_N[1] \end{bmatrix}, \ldots \\
\mapsto \{x_1[0], \ldots, x_N[0], x_1[1], \ldots, x_N[1], \ldots\}.
\]

By definition, discrete-time lifting \(\mathbf{L}_N\) converts a one-dimensional signal with sampling period \(h/N\) to a \(N\)-dimensional signal with sampling period \(h\). Also, discrete-time lifting preserves the \(\ell^2\) norm. By using \(\mathbf{L}_N\) and \(\mathbf{L}_N^{-1}\), we obtain a norm-equivalent discrete-time LTI system for time-varying \(S_{h/N}T_{zw}H_{h/N}\).

Let \(c2\) denote the step-invariant transformation [1], that is,
\[
c2 \left( \begin{bmatrix} A & B \\ C & D \end{bmatrix}, h \right) := S_h \left[ \begin{bmatrix} A & B \\ C & D \end{bmatrix} \right] H_h = \left[ e^{Ah} \int_0^h e^{At} B dt \right].
\]

and lift denote the discrete-time lifting transformation [1], that is,
\[
lift \left( \begin{bmatrix} A & B \\ C & D \end{bmatrix}, N \right) := \mathbf{L}_N \left[ \begin{bmatrix} A & B \\ C & D \end{bmatrix} \right] \mathbf{L}_N^{-1} = \begin{bmatrix} A^N & A^{N-1}B & A^{N-2}B & \ldots & B \\ C & D & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C & A & D & 0 & \ldots \\ C & A^{N-1} & C \ldots & C^{N-3}B & C^{N-2}B & \ldots & D \end{bmatrix}.
\]

Then we have the following theorem:

Theorem 3: Assume that \(L = mh + \frac{1}{N}k\) for some integers \(m \geq 0\) and \(k \in \{0, \ldots, N-1\}\). Then, for FSFH approximation \(S_{h/N}T_{zw}H_{h/N}\), there exists a discrete-time LTI generalized plant \(\Sigma_{dN}\) such that
\[
\|S_{h/N}T_{zw}H_{h/N}\|_{\infty} = \|\mathbf{F}(\Sigma_{dN}, K)\|_{\infty},
\]
where the \(H^\infty\) norm is defined by the \(\ell^2\)-induced norm. Moreover, norm-equivalent \(\Sigma_{dN}\) is given by
\[
\Sigma_{dN} := \begin{bmatrix} W_{dN} \\ S_{dN}W_{dN} \end{bmatrix}, \begin{bmatrix} -H_N \\ S_{N,k}z^{-m}P_{dN}G_{dN}H_N \end{bmatrix},
\]
where
\[
W_{dN} := \lift(c2d(W, h/N), N), \\
P_{dN} := \lift(c2d(P, h/N), N), \\
G_{dN} := \lift(c2d(G, h/N), N), \\
H_N = \begin{bmatrix} 1, 1, \ldots, 1 \end{bmatrix}^T, \quad S_N = \begin{bmatrix} 1, 0, \ldots, 0 \end{bmatrix}, \\
S_{N,k} = \begin{bmatrix} 0 & 0 & \ldots & 0 & 1 & 0 & \ldots & 0 \end{bmatrix}^T.
\]

Proof: The formulae are obtained by the method described in [1, Chap. 8].
Note that $W_{dN}$, $P_{dN}$, and $G_{dN}$ are LTI. Finally, our problem is reduced to a standard discrete-time $H^\infty$ control problem with the LFT shown in Fig. 8. In this figure,

$$\dot{z}_d := L_N z_d, \quad w_d := L_N w_d, \quad y_d := S_h y,$$

and $u_d$ is the output of the controller $K(z)$. Then the optimal controller $K(z)$ for this standard $H^\infty$ control problem is easily obtained by using `hinfsyn` function in MATLAB Robust Control Toolbox.

### 5. SIMULATION

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

We assume that sampling period $h$ is normalized to 1. The coupling wave path is modeled by

$$P(s) = \frac{0.25}{s+1},$$

with time delay $L = 1$, that is, the time delay is equal to the sampling period $h$. The relay station is modeled by $G(s) = 2.5$, that is, the station amplifies input signals by 8 [dB].

For these parameters, we first design a feedforward canceler proposed in Section 2. We assume the frequency characteristic of input signals is given by

$$F(s) = \frac{1}{2s+1}.$$

Note that the magnitude of $F(j\omega)$ represents the envelope of the spectra of the input signals (e.g. rectangular waves). The discretization parameter for FSFH is set to $N = 16$. The obtained $H^\infty$-optimal $K(z)$ is of 18-th order. With this filter, we simulate coupling wave canceling with a periodic rectangular wave input with period $8h$. Note that this signal contains frequency components beyond the Nyquist frequency, $\pi/h = \pi$ [rad/sec], although the frequency of the periodic wave, $\pi/8h = \pi/8$ [rad/sec] is much lower than $\pi$.

Fig. 9 shows the reconstructed signal $y$ (see Fig. 2) by the proposed feedforward canceler, the input signal $v$, and the signal $y$ with no canceler. This result shows that the feedforward canceler works well. To see this more precisely, we compute the effect of the coupling wave,

$|y(t) - v(t)|$, which is shown in Fig. 10. This result shows the proposed canceler well cancels the self-interference.

A drawback of the feedforward canceler is that it never works if the gain of $G(s)$ is so high that the feedback loop is unstable. For example, if we take $G(s) = 1000$, that is, the relay station amplifies input signals by 60 [dB], then the feedback loop becomes unstable. For this situation, we adopt a feedback canceler proposed in Section 3. The frequency characteristic $W(s)$ is assumed to be the same as $F(s)$, that is, $W(s) = F(s) = 1/(2s+1)$. The other parameters are the same as those for the feedforward canceler design. With FSFH discretization number $N = 16$, we compute the $H^\infty$-optimal $K(z)$ by the method described in Section 4.

Fig. 11 shows the reconstructed signal $u$ in the feedback canceler (see Fig. 4). Note that with any feedback canceler, the signal should diverge because the feedback loop around the relay station itself is unstable. On the other hand, the feedback canceler shows small reconstruction error as shown in Fig. 12.
In summary, by the simulation results, sampled-data $H^\infty$ optimal design is proved to be effective for coupling wave canceling.

6. CONCLUSIONS

In this article, we have proposed feedforward/feedback cancelers based on the sampled-data $H^\infty$ control theory. The design of feedforward cancelers is reduced to a sampled-data $H^\infty$ optimal discretization problem, while that of feedback cancelers is formulated by a standard sampled-data $H^\infty$ control problem. They can be numerically solved by the FSFH method. Simulation results have been shown to illustrate the effectiveness of the proposed feedforward/feedback cancelers. Future work may include FIR (Finite Impulse Response) filter design as proposed in [7], adaptive FIR filtering as proposed in [5], robust filter design against uncertainty in the coupling wave path, and implementation of the designed filter.

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