New Interference Estimation for Power Control in Wireless Networks

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Abstract – This paper proposes new interference estimation for power control in broadband wireless data networks. The proposed approach gives the filtered interference power in real-time removing undesired effects such as the fluctuation of interference power and the measurement noise due to receiver noise. The well-known Finite Impulse Response (FIR) structure filter is adopted for both the interference and the noise covariance estimation. The proposed mechanism provides both the filtered interference power and the filtered number of active co-channel interferers, which shows good inherent properties. And the filtered interference power is not affected by the constant number of active co-channel interferes. It is also shown that the filtered number of active co-channel interference is separated from the filtered interference power. From discussions about the choice of design parameters such as window length and covariance ratio, they can make the estimation performance of the proposed FIR filtering based mechanism as good as possible. Via extensive computer simulations, the performance of the proposed mechanism is shown to be superior to the existing Kalman filtering based mechanism.

Key words – power control; interference estimation; FIR filtering; Kalman filtering

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1 Introduction

The fundamental objective of power control in wireless data networks is for each user to transmit enough power so that it can achieve the required Quality of Service (QoS) without causing unnecessary interference to other users in the system. The power control has been shown to be a useful technique to compensate for path loss and co-channel interference in Time Division Multiple Access (TDMA) wireless networks. Moreover, in Code Division Multiple Access (CDMA) wireless networks, the situation is more complicated due to the near-far effect and the intracell interference. Therefore, various classes of power control problems have been formulated in the past few years[1-8].

Recently, among existing mechanisms, the Kalman filtering based interference estimation mechanism for power control has been made by posing the optimal filtering problem due to the compact representation and the efficient manner[5-8]. However, the Kalman filter has an Infinite Impulse Response (IIR) structure that utilizes all past measurements accomplished by equaling weighting and has a recursive formulation. Thus, the Kalman filter tends to accumulate the filtering error as time goes and can show even divergence phenomenon for temporary modeling uncertainties and round-off errors[9-12]. In addition, to estimate covariances for the process noise and measurement noise, existing mechanisms utilizes only finite measurements on the most recent window. This means estimated noise covariances have a FIR structure, which could be somewhat inconsistent with the Kalman filtering with the IIR structure. Therefore, in the current paper, an alternative interference estimation mechanism is proposed to predict the future interference-plus-noise power. The proposed mechanism gives the filtered interference power in real-time removing undesired effects such as the fluctuation of interference power and the measurement noise due to receiver noise. For the filtering, the proposed mechanism adopts the FIR structure filter that utilizes only finite measurements on the most recent window. In addition, estimated noise covariances also have the FIR structure and thus utilize only finite measurements on the same window. Thus, there can be consistency between the interference estimation and the noise covariance estimation. The proposed mechanism provides the filtered interference power as well as the filtered number of active co-channel interferers. The filtered interference power has good inherent properties such as unbiasedness, efficiency, deadbeat, and robustness due to the FIR structure. It is shown that the filtered interference power is not affected by the constant number of active co-channel interferes. It is also shown that the filtered number of active co-channel interferers is separated from the filtered interference power. These remarkable properties cannot be obtained from the Kalman filtering based mechanism in Ref. [5-8].

Since the choice of an appropriate window length and covariance ratio is important issue to make the performance of the proposed FIR filtering based mechanism as good as possible, some discussions about these parameters will be done. From above discussions, it can be stated that both the window length and the covariance ratio can be considered as useful design parameters to make the filter-

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ing performance as good as possible. Finally, via extensive computer simulations, the performance of the proposed FIR filtering based mechanism is shown to be superior to the existing Kalman filtering based mechanism.

The paper is organized as follows. In section 2, a new interference estimation mechanism is proposed. In section 3, remarkable properties of the proposed mechanism are shown. In section 4, the choice of the window length and the covariance ratio is discussed. In section 5, extensive simulations are performed to verify the proposed mechanism. Finally, conclusions are made in section 6.

2 New interference estimation mechanism

The interference power is modeled by the following second order state space model as shown in Ref. [5-8]

$$\begin{aligned} \boldsymbol{x}(k+1) &= \Phi\boldsymbol{x}(k) + \boldsymbol{w}(k), \\ z(k) &= \Phi\boldsymbol{x}(k) + \boldsymbol{v}(k), \end{aligned} \quad (1)$$

where

$$\boldsymbol{x}(k) = \begin{bmatrix} x_i(k) \\ x_n(k) \end{bmatrix}, \boldsymbol{w}_k = \begin{bmatrix} w_i(k) \\ w_n(k) \end{bmatrix}, \Phi = \boldsymbol{I}.$$

The state $x_i(k)$ represents the actual interference power and the state $x_n(k)$ represents the number of active co-channel interferers for time slot k, respectively. The measurement $z(k)$ represents the measured interference power for time slot k. The process noise $\boldsymbol{w}(k)$ is due to fluctuation of interference power as terminals start new transmissions and/or adjust their transmission power in the time slot. The measurement noise $\boldsymbol{v}(k)$ is due to receiver noise. These noises are white noise sequences with covariances $\boldsymbol{Q}(k)$ and $\boldsymbol{R}(k)$, respectively.

The main task of the proposed interference estimation mechanism is the filtering of interference power in real-time removing undesired effects such as the fluctuation of interference power and the measurement noise due to receiver noise. For the filtering, the well known FIR filter in Ref. [11-15] is adopted. For the state space model (1), the FIR filter $\hat{\boldsymbol{x}}(k)$ processes linearly the only finite measurements on the most recent window $[k-N, k]$ as the following simple form

$$\hat{\boldsymbol{x}}(i) = \begin{bmatrix} \hat{x}_i(k) \\ \hat{x}_n(k) \end{bmatrix} = \boldsymbol{H}\boldsymbol{Z}_M(k) = \begin{bmatrix} H_i \\ H_n \end{bmatrix} \boldsymbol{Z}_M(k), \quad (2)$$

where the gain matrix $\boldsymbol{H}$ and the finite measurements $\boldsymbol{Z}_M(k)$ are represented by

$$\boldsymbol{H} \equiv [h(M) \quad h(M-1) \quad \cdots \quad h(0)], \quad (3)$$

$$\boldsymbol{Z}_M(k) \equiv [z^{\mathrm{T}}(K-M) \quad z^{\mathrm{T}}(k-M+1) \quad \cdots \quad z^{\mathrm{T}}(k)]^{\mathrm{T}}. \quad (4)$$

At the current time slot k, the algorithm for filter gain coefficients $h(\cdot)$ in Eq. (3) is obtained from the following algorithm as shown in Ref. [11-15]

$$h(j) = \Omega^{-1}(M)\Psi(l)R^{-1}(k-M+j), \quad (5)$$

where

$$\Psi(l+1) = \Psi(l)[I + \Omega(M-l-1)Q(k-M+l)]^{-1}, \quad (6)$$

$$\Omega(l+1) = [I + \Omega(l)Q(k-M+l)]^{-1}\Omega(l) + R^{-1}(k-M+l), \quad (7)$$

and

$$\Psi(0) = I, \Omega(0) = R^{-1}(k-M),$$
$$0 \leqslant j \leqslant M, 0 \leqslant l \leqslant M-1.$$

The finite measurements $\boldsymbol{Z}_M(\mathrm{k})$ in Eq. (4) can be represented in the following regression form

$$\boldsymbol{Z}_M(k) = L_M x_i(k-M) + N_M X_n(k) + G_M W(k) + V(k), \quad (8)$$

where $x_n(k), W(k), V(k)$ have the same form as Eq. (4) for $x_n(k), w(k), v(k)$, and matrices $\boldsymbol{L}_M, \boldsymbol{N}_M, \boldsymbol{G}_M$, are defined by

$$\boldsymbol{L}_M = \begin{bmatrix} I \\ I \\ \vdots \\ I \end{bmatrix},$$

$$\boldsymbol{N}_M = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ I & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ I & I & \cdots & I & 0 \end{bmatrix},$$

$$\boldsymbol{G}_M = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ I & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ I & I & \cdots & I & 0 \end{bmatrix}, \quad (9)$$

Noise covariances $Q(k)$ and $P(k)$ need to be estimated as inputs for Eq. (5)~Eq. (7). As shown in Ref. [8], noise covariances are estimated using the only finite interference measurements on the most recent window $[k-N, k]$ as follows

$$Q(k) = \frac{1}{M}\sum_{j=k-M}^{k}[z(j) - \bar{z}(k)]^2, \quad (10)$$

$$R(k) = \gamma Q(k), 0 < \gamma < 1, \quad (11)$$

$$\bar{z}(k) = \frac{1}{M+1}\sum_{j=k-M}^{k} z(j), \quad (12)$$

where γ will be called the covariance ratio. Since the standard deviation of the interference power can reach as much as tens of decibels, which is much higher than typical measurement errors, $Q(k)$ in Eq. (10) gives a good covariance estimation for the process noise. In addition, the choice of $R(k)$ in Eq. (11) with γ less than 1 is reasonable because the measurements noise is likely to be proportional to the fluctuation of interference power. A practical guidance on the choice of a window length M and a covariance ratio γ will be discussed in Section 4, to make the performance of the proposed FIR filtering based mechanism as good as possible.

Note here that estimated noise covariances Eq. (10) and Eq. (11) also have the FIR structure because only finite interference measurements on the most recent window $[k-N, k]$ are utilized like the interference estimation filter of Eq. (2). Therefore, it can be stated that the proposed mechanism has the onsistency between the interference estimation and the noise covariance estimation, while the existing Kalman filtering based mechanism does not.

3 Remarkable properties

Ultimately, the filtered interference power $\hat{x}_i(k)$ is obtained from Eq. (2) as follows

$$\hat{x}_i(k) = H_i Z_M(k). \tag{13}$$

The filtered interference power $\hat{x}_i(k)$ has good inherent properties of unbiasedness, efficiency, and deadbeat since the FIR filter in Ref. [11-15] provides these properties. The Kalman filter used in Ref. [5-8] does not have these properties unless the mean and covariance of the initial state is completely known. Among them, the remarkable one is the deadbeat property which the filtered interference power $\hat{x}_i(k)$ tracks the actual interference power $x_i(k)$ exactly in the absence of noises. The deadbeat property gives the following matrix equality as shown in Ref. [11-12]

$$H\begin{bmatrix} I \\ \Phi \\ \Phi^2 \\ \vdots \\ \Phi^M \end{bmatrix} = \Phi^M,$$

and then

$$\begin{bmatrix} H_i \\ H_n \end{bmatrix}[L_M \quad \bar{N}_M] = \begin{bmatrix} I^M & MI \\ 0 & I \end{bmatrix},$$

where $\bar{\boldsymbol{N}}_M = [0 \quad \boldsymbol{I} \quad 2\boldsymbol{I} \quad \cdots \quad \boldsymbol{MI}]^{\mathrm{T}}$. Therefore, the following matrix equalities are obtained:

$$H_i L_M = I, H_i\bar{\boldsymbol{N}}_M = \boldsymbol{MI},$$
$$H_n L_M = 0, H_n\bar{\boldsymbol{N}}_M = 1, \tag{14}$$

which gives following remarkable properties.

It will be shown in the following theorem that the filtered interference power $\hat{x}_i(k)$ in Eq. (13) is not affected by the number of active co-channel interferers when the number of active co-channel interferers is constant on the measurement noise $[k-N,k]$.

Theorem 1: When the number of active co-channel interferers is constant on the measurement window $[k-N,k]$, the filtered interference power $\hat{x}_i(k)$ in Eq. (13) is not affected by the number of active co-channel interferers.

Proof: When the number of active co-channel interferers is constant as $\bar{x}_n$ on the measurement window $[k-N,k]$, the finite measurements $Z_M(k)$ in Eq. (8) can be represented in

$$\begin{aligned} &Z_M(k) \mid \{x_n(k) = \bar{x}_n \text{ for } [k-M,k]\} = \\ &L_M x_i(k-M) + \bar{N}_M \bar{x}_n + G_M W(k) + V(k). \end{aligned} \tag{15}$$

Then, the filtered interference power $\hat{x}_i(k)$ for output voltage is derived from Eq. (13)~Eq. (15) as

$$\begin{aligned} &\hat{x}_i(k) = H_i - Z_m(k) = \\ &H_i[L_M x_i(k-M) + \bar{N}_M \bar{x}_n + \\ &G_M W(k) + V(k)] = \\ &H_i L_M x_i(k-M) + H_i \bar{N}_M \bar{x}_n + \\ &H_i[G_M W(k) + V(k)] = \\ &x_i(k-M) + MI\bar{x}_n + \\ &H_i[G_M W(k) + V(k)]. \end{aligned} \tag{16}$$

From Eq. (1), the actual interference power $x_i(k)$ can be represented on $[k-N,k]$ as follow

$$\hat{x}_i(k) \mid \{x_n(k) = \bar{x}_n \text{ for } [k-N,k]\} =$$
$$x_i(k-M) + MI\bar{x}_n + \bar{\boldsymbol{G}}_M W(k), \tag{17}$$

where $\bar{\boldsymbol{G}}_M = [\boldsymbol{I} \quad \boldsymbol{I} \quad \cdots \quad \boldsymbol{I} \quad 0]$. Thus, using Eq. (16) and Eq. (17), the error of the filtered interference power $x_i(k)$ is

$$\begin{aligned} &\hat{x}_i(k) - x_i(k) = \\ &H_i[G_M W(k) + V(k)] + \bar{\boldsymbol{G}}_M W(k), \end{aligned}$$

which does not include the term for the number of active co-channel interferers. This completes the proof.

The number of active co-channel interferers itself can be treated as variable which should be filtered. In this case, the filtered number of active co-channel interferers is shown to be separated from the filtered interference power term.

Theorem 2: The filtered number of active co-channel interferers $\hat{x}_n(k)$ in Eq. (2) is separated from the filtered interference power term.

Proof: The filtered number of active co-channel interferers $\hat{x}_n(k)$ is derived from Eq. (2) and Eq. (14) as

$$\begin{aligned} &\hat{x}_n(k) = H_n Z_M(k) = \\ &H_n[L_M x_i(k-N) + N_M X_n(k) + \\ &G_M W(k) + V(k)] = \\ &H_n[N_M X_n(k) + G_M W(k) + V(k)], \end{aligned}$$

which does not include the filtered interference power term. This completes the proof.

Above remarkable properties of the proposed FIR filtering based mechanism cannot be obtained from the existing Kalman filtering based mechanism in Ref. [5-8]. In addition, as mentioned previously, the proposed mechanism has the deadbeat property, which means the fast tracking ability of the proposed mechanism. Furthermore, due to the FIR structure and the batch formulation, the proposed mechanism might be robust to temporary modeling uncertainties and to round-off errors, while the Kalman filtering based mechanism might be sensitive for these situations.

4 Choice of window length and covariance ratio

The important issue here is how to choose an appropriate window length M and covariance ratio γ to make the filtering performance as good as possible. They affect differently the performance of the proposed FIR filtering based mechanism.

The noise suppression of the proposed mechanism might be closely related to the window length M. The proposed mechanism can have greater noise suppression as the window length M increases, which improves the filtering performance of the proposed mechanism. However, in case of too large window length M, the real-time application is somewhat difficult due to the computational load. This illustrates the proposed mechanism's compromise between the noise suppression and the computational load. Since M is an integer, fine adjustment of the properties with M is difficult. Moreover, it is difficult to determine the window length is systematic ways. In applications, one way to determine the window length is to take the appropriate value that can provide enough noise suppression.

The tracking ability of the proposed mechanism might be closely related with the covariance ratio γ when the window length M is determined. When the window length is fixed, the tracking ability of a filter increases and the noise-suppressing ability decreases as γ increases, and vice versa. Thus, γ is also a useful parameter in the adjustment of the tracking and noise-suppressing properties of the FIR filtering based mechanism.

Therefore, it can be stated from above discussions that both the window length M and the covariance ratio γ can be considered as useful parameters to make the performance of the proposed FIR filtering based mechanism as good as possible.

5 Extensive computer simulations

The performance of the proposed FIR filtering based interference estimation mechanism is evaluated via extensive computer simulations. The proposed mechanism will be compared with the Kalman filtering based mechanism[5-8].

For both mechanisms, the covariance ratio is taken by three cases, $\gamma = 0.1$, $\gamma = 0.5$, $\gamma = 0.9$. For the proposed mechanism, the window length is taken by three cases, $M = 5$, $M = 10$, $M = 20$. The initial state estimate is taken by $\hat{\boldsymbol{x}}(k_0) = [0 \quad 0]^T$ as shown in existing works[5-8]. The existing Kalman filtering based mechanism assumes that a priori information is exactly known. However, this assumption would be unpractical because any state should be considered not measurable and thus unknown for state estimation problems. On the other hand, the proposed FIR filtering based mechanism does not require the initial state estimate as shown in Eq. (2). To make a clearer comparison, thirty Monte Carlo runs are performed and each single run lasts for 200 samples. For all window lengths and covariance ratios, Tab. 1 shows mean values for Root-Mean-Square (RMS) errors of the filtered interference power.

For $M = 10$ and $\gamma = 0.5$, Fig. 1 and 2 show the plots for Root-Mean-Square (RMS) errors of the filtered interference power and the filtered number of active co-channel interferers. These simulation results show that the performance of the proposed FIR filtering based mechanism is superior to the existing Kalman filtering based mechanism.

Tab. 1 Mean of RMS error for two mechanisms

	Proposed mechanism			Existing mechanism
	$M = 5$	$M = 10$	$M = 20$	
$\gamma = 0.1$	0.038 4	0.038 2	0.035 4	0.106 1
$\gamma = 0.5$	0.032 5	0.032 3	0.030 6	0.099 7
$\gamma = 0.9$	0.033 5	0.033 3	0.031 9	0.101 0

6 Conclusion

This paper has proposed the new interference estimation for power control in broadband wireless data networks. The proposed mechanism gives the filtered interference power in real-time removing undesired effects such as the fluctuation of interference power and the measurement noise due to receiver noise. The well known FIR structure is adopted for the interference estimation as well as the noise covariance estimation. The proposed mechanism provides both the filtered interference power and the filtered number of active co-channel interferers, which shows good inherent properties. It is shown that the filtered interference power is not affected by the constant number of active co-channel interferes.

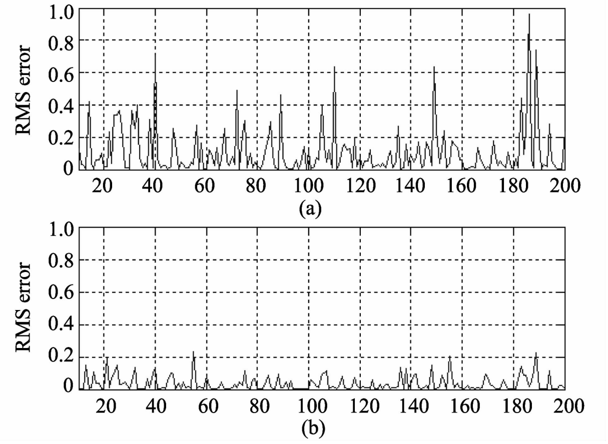

Fig. 1 Filtered interference power: (a) Existing mechanism, (b) Dropsed mechanism

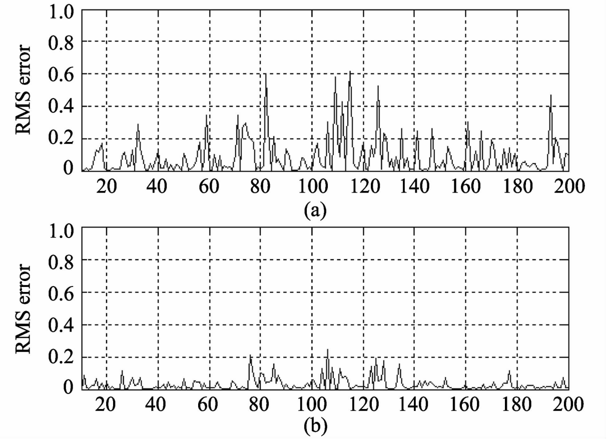

Fig. 2 Filtered number of active co-channel interferers: (a) Existing mechanism, (b) Proposed mechanism

It is also shown that the filtered number of active co-channel interferers is separated from the filtered interference power. From discussions about the choice of design parameters such as window length and covariance ratio, it is shown that they can make the estimation performance of the proposed FIR filtering based mechanism as good as possible. The performance of the proposed mechanism is shown to be superior to the existing Kalman filtering based mechanism via computer simulations.

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