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Brief paper

Power control in Wireless Cellular Networks with a time-varying delay[☆]

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ABSTRACT

Uplink transmission power control is an essential task in Wireless Cellular Networks (WCNs) due to the resource limitation of the Mobile Stations (MSs). One remaining problem is the effect of the delay caused by measuring the signal strength and decision making in the Inner-Loop Power Control (ILPC). In this article, we develop the Potential Feedback Controller (PFC) for a linear scalar discrete-time system with disturbance in order to take into account an unknown bounded time-varying input delay for uplink ILPC. The main interest of the PFC is to treat easily a stabilization problem with a constraint on the state space by using a nonlinear feedback control with a short computation time. Simulations illustrate that by applying the PFC, the communication connectivity is ensured by maintaining the signal strength above a required limit.

1. Introduction

Power control in WCNs is a key degree of freedom in the management of interference, energy and connectivity (Chiang, Hande, Lan, & Tan, 2008). In uplink transmission, energy efficiency aspect of power control is more dominant due to the limited energy resource of the Mobile Station (MS). Uplink power control in WCNs includes two main objectives (Alpcan, Başar, Srikant, & Altman, 2002; Castro, 2001; Sesia, Toufik, & Baker, 2009):

- firstly, to ensure the communication connectivity by setting up a power controller to keep the received signal strength above a limit below which the communication is interrupted.
- secondly, to minimize the overall transmitted power in a cell in order to minimize the interferences between users and to maximize the battery life of the MS.

Principally, power control in WCNs consists of an open-loop power control and a closed-loop power control schemes (Chiang et al., 2008). In open-loop power control, the Base Station (BS) selects the transmit power control by exploiting the estimated channel condition like distance-dependent attenuation and frequency-independent slow fading at the MS based on the received signal strength of a pilot signal transmitted by the BS (Laiho, Wacker, & Novosad, 2006).

The closed-loop power control itself consists of two different loops: Inner-Loop Power Control (ILPC) and Outer-Loop Power Control (OLPC) (Gunnarsson, Gustafsson, & Blom, 2001; Laiho et al., 2006). In ILPC, the received signal strength is compared to a target value at the BS. If the measured signal strength is higher (lower) than the target value, the BS will send a control signal to the MS in order to decrease (increase) the transmission power. The ILPC should be repeated fast enough to cover the fast fading effect. The OLPC (which is slower than the ILPC) provides the target signal strength based on the Quality of Service (QoS) requirements in the higher layers (Laiho et al., 2006). In this paper, we are interested in the ILPC.

Transmitting and measuring signals and decision making take time which results in time delays in the closed-loop power control. The main reasons of these delays come from the power control algorithm itself; time for computing and decision making; time to transmit the power control command to the MS (Chiang et al., 2008; Holma & Toskala, 2009; Luna-Rivera & Campos-Delgado, 2013). According to the time-varying behavior of the transmission channel quality, load of the MSs and the size of the packets to be sent in a realistic scenario, a time-varying delay in the closed-loop power control must be considered. The delay in uplink ILPC is discussed further in Section 2. Like every feedback control loop, the ILPC will be affected by this time-varying delay. In fact, the power control is more sensitive to the delay than to the signal strength estimator (Gunnarsson et al., 2001).

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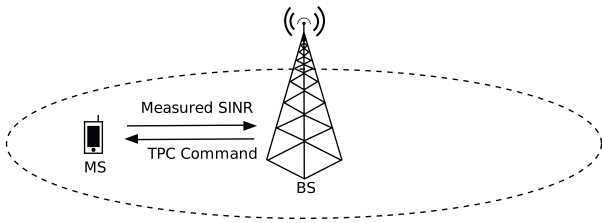

Fig. 1. Uplink ILPC between a MS and a BS.

Stability of the OLPC in the presence of communication delays has been studied in Feyzmahdavian, Johansson, and Charalambous (2012), Sung and Leung (2005), Yates (1995). In Gunnarsson et al. (2001), the authors proposed a control scheme to highlight the dynamical behavior of the ILPC subject to a constant delay where they proposed a time-delay compensation (TDC) in order to mitigate the oscillations due to the delay. In our paper, we develop the PFC first proposed in Phan, Moulay, Coirault, Launay, and Combeau (2015) in order to take into account an unknown bounded time-varying input delay for uplink ILPC in WCNs. To the best of our knowledge, this is the first time that a solution for the time-varying delay in the ILPC of WCNs has been proposed.

The remainder of the paper is organized as follows. The system model is described in Section 2. In order to take into account a time-varying input delay, the PFC is developed in Section 3. It is applied and simulated for a WCN using the Long-Term Evolution (LTE) communication standard and compared with the existing Transmission Power Control (TPC) algorithm in Section 4. Finally, a conclusion is addressed in Section 5.

2. Modeling

In our article, we are interested in the uplink ILPC of a cell with a MS denoted by k and a BS denoted by i which is illustrated in Fig. 1. The received Signal-to-Interference-plus-Noise Ratio (SINR) is commonly used in wireless communication to measure the transmission quality. For simplicity, we neglect the intra-cell interferences (in communication standards like LTE and 802.11n, the use of, respectively, OFDMA and OFDM avoids the intra-cell interferences Khan, 2009). Therefore, after frequency synchronization, only the inter-cell interferences affect the SINR in the model. The received SINR at the BS i of the transmitted signal from the MS k is given by

$$\chi_{ik}(n) = \frac{g_{ik}(n)p_{ik}(n)}{\sum_{l\neq k} g_{il}(n).p_{il}(n) + \sigma_{ik}^2(n)} \tag{1}$$

where p_{ik} is the transmitted power; g_{ik} the channel gain by which the signal between the transmitter k and the receiver i is attenuated and it can be modeled by three components: path-loss, log-normal shadowing and multi-path fading (Rappaport, 2001); σ_{ik}^2 the thermal noise affecting the channel between the MS k and the BS i; n represents the ILPC sample time. The term $\sum_{l\neq k} g_{il}(n).p_{il}(n)$ corresponds to the inter-cell interferences. As it has been assumed that the intra-cell interferences are neglected, we can rewrite (1) as follows:

$$\chi_{ik}(n) = \frac{g_{ik}(n).p_{ik}(n)}{i_{ik}(n) + \sigma_{ik}^2(n)} \tag{2}$$

where $i_{ik}(n) = \sum_{l\neq k} g_{il}(n).p_{il}(n)$ are the inter-cell interferences. Let us define the pathloss pl between the MS k and the BS i by $pl_{ik}(n) = \frac{1}{g_{ik}(n)}$ and $i_o t_{ik}(n) = \frac{(i_{ik}(n)+\sigma_{ik}^2(n))}{\sigma_{ik}^2(n)}$. We can rewrite (2) as follows:

$$\chi_{ik}(n) = \frac{p_{ik}(n)}{pl_{ik}(n).\sigma_{ik}^2(n).i_o t_{ik}(n)}. \tag{3}$$

In the following, we rewrite the received SINR equation in the logarithmic domain in dB. Consequently, Eq. (3) becomes

$$x_{ik}(n) = P_{ik}(n) - PL_{ik}(n) - \Sigma_{ik}^2(n) - I_o T_{ik}(n). \tag{4}$$

Uplink ILPC in WCNs

In uplink ILPC, the SINR is estimated at the MS and it is sent to the BS where it will be compared with a SINR_{min} which is the minimum required value of SINR to maintain the communication connectivity. Based on its difference with the SINR_{min}, a TPC command is sent to the MS to update the transmission power (Gunnarsson et al., 2001; Muhammad & Mohammed, 2009; Sheth & Han, 2003). So we can describe this procedure as follows:

- Receiver (BS):

$$\begin{aligned} err_i(n) &= x_{ik}(n) - x_{min} \\ u_i(n) &= f(err_i(n)) \end{aligned} \tag{5}$$

where x_{min} is the SINR_{min}; err_i the difference between the available measured SINR at the sample time n and the SINR_{min}; u_i the TPC command computed at the BS to be sent to the MS which is a function of the err_i as it is explained above. The SINR_{min} is provided by the OLPC at a lower update rate based on the required value of the Block Error Rate (BLER) in higher layers (Chiang et al., 2008). Hence, this value may be regarded constant for the ILPC. There exist different algorithms based on the different communication standards applied in WCNs (Gunnarsson et al., 2001; Muhammad & Mohammed, 2009; Sheth & Han, 2003). For example in LTE, the TPC command u_i can vary between $[-1; 3]$ dBm (for more information see (Muhammad & Mohammed, 2009)). In Section 4, we will compare the PFC with taking into account an unknown bounded time-varying input delay with an existing TPC algorithm in LTE communication standard.

- Transmitter (MS):

Evolution of the transmit power at the MS is given by the following equation:

$$P_{ik}(n+1) = P_{ik}(n) + u_i(n - \tau(n)) \tag{6}$$

where P_{ik} is the transmit power adjustment. It should be taken into account that the computed uplink transmit power should not exceed the maximum MS transmit power P_{max} (Castellanos et al., 2008; Chiang et al., 2008). For simplicity, we do not take into account the P_{max} in our calculation but we will take it into account in our simulations in Section 4.

Both measuring and signaling in cellular systems take time, which results in delayed signals. Here are the main reasons for the existence of time delay in power control update in WCNs (Chiang et al., 2008):

– the power control algorithm itself results in a delay of one sample time since the power control at sample time n is used to update the power level at sample time $n + 1$;

– it takes certain amount of time to measure the SINR and generate a power control decision at the BS;

– the power control update is only allowed to be transmitted at certain time instants;

– the time that it takes to transmit the power control command from the BS to the MS.

As it has been explained in Section 1, this delay $\tau(n)$ must be considered as a time-varying delay. The capacity of the network and the details of the communication standard are known, therefore the maximum and minimum values of $\tau(n)$ are known too:

$$0 < h_1 \leq \tau(n) \leq h_2 \tag{7}$$