A Phase-Locked Loop Clock Synchronization Method Combined with Discrete Spectrum Correction

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Keywords: Wireless sensor networks, Clock synchronization, Signal process, Phase-locked loop, Physical layer.

Abstract： The main purpose of this paper is to achieve clock synchronization between physical layers of network nodes, and to achieve frequency synchronization and full synchronization by exchanging clock information through pulse-coupled discrete time phase-locked loop. This article is mainly to use the discrete spectrum correction method to reduce the influence of noise caused by crystal oscillator clock signal in transmission process due to various reasons, then establish Laplacian matrix which consist of relative signal intensity of nodes to control the update amount of clock information, finally the synchronization steady state between network nodes is achieved.

1 INTRODUCTION

Wireless sensor network (WSN) is a large-scale, self-organizing and multi-hop distributed sensor network which can achieve data acquisition, processing and transmission. It consists of many sensor nodes and each node is timed by a local clock module which is usually provided by a crystal oscillator. Due to the independence, physical dispersion of node, the error of crystal frequency is to be different, then the local clock between nodes are asynchronous that affect the data processing. So there are many time synchronization technologies. Time synchronization determines the service quality of wireless sensor network, and it is important to improve the quality and efficiency of people's life.

Time synchronization technology has been a focus in wireless communication field. Many kinds of time synchronization algorithms have been studied to reduce power consumption, complexity, and improve accuracy. The common network time synchronization (NTP) in computer is to synchronize the clock to world coordination time UTC, which can provide high precision of time correction. NTP propagate (Mills D. 1992) according to the rank of server, and the hierarchical structure is divided according to the distance, but it can't meet the requirements of low power consumption, limited bandwidth and wireless transmission, so it's not suitable for wireless sensor networks. The traditional time synchronization protocol has reference broadcast synchronization mechanism (RBS) based on receiving to receiving mode, the delay measurement time synchronization DMTS (Ping S. 2003) based on sending to receiving unidirectional mode, the TPSN based on sending to receiving bi-directional mode. A new time synchronization technology is firefly synchronization (Hailei Zhao. 2015). The interaction between fireflies is modeled as electric coupling. The coupling start and it changes the state quantity, while the state variable changes the phase quantity. The phase difference is reduced by synchronization process, finally caused the full synchronization. Synchronization can be done directly in the physical layer without the need for message transmission and the synchronization accuracy is not affected by MAC delay, protocol processing, etc.

Therefore, this paper analyzes the frequency and phase synchronization as clock synchronization on the basis of physical layer. Because in the transmission process, the signal of crystal oscillator will cause noise due to various factors, so we use the signal processing method of asymmetric window in discrete spectrum to reduce the influence of noise on signal. Then a discrete time clock model is established. Due to the information exchange by coupling clock, the update of node clock is link with other nodes in network. According to the network

Wu, Y., Xu, X., Li, K., Hu, Y. and Han, K.
A Phase-Locked Loop Clock Synchronization Method Combined with Discrete Spectrum Correction.
In *3rd International Conference on Electromechanical Control Technology and Transportation (ICECTT 2018)*, pages 228-231
ISBN: 978-989-758-312-4

topology, the relative signal strength between nodes is defined, and then established Laplacian matrix to control update of node clock, finally realize the stable synchronous state.

2 DISCRETE SPECTRUM SIGNAL PROCESSING

The clock node in network is a time measuring device which composed of an oscillator and a battery. Due to various reasons in transmission process, the discrete time clock affected by noise, so this paper choose signal processing method of asymmetric window correction(MBAW) to process noise. The asymmetric window is built by cutting the symmetric window with a straight line which used the original point. It can get some properties of asymmetric window through simulation comparison between asymmetric window and corresponding symmetric window. For simplify the description of asymmetric window function, it use A- Hanning window to show asymmetric hanning window in fig.1, fig.2 and fig.3 is similar.

From fig.1, fig.2, fig.3, It can be concluded that asymmetric and symmetric window with the same amplitude characteristics, the attenuation rate of side lobe envelope is almost agreement, and phase line of symmetrical window and corresponding asymmetric window is always intersect in center of main valve which lays the theoretical foundation for the asymmetric window phase difference algorithm.

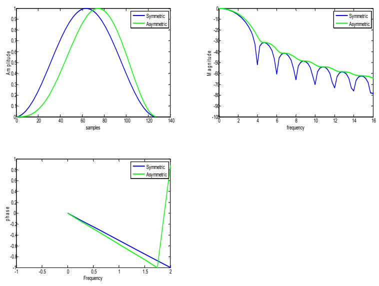

Figure 1: Hanning window and A-hanning windonw.

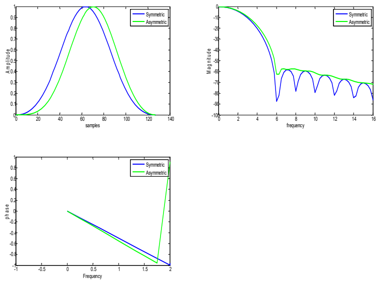

Figure 2: Blackman window and A-blackman window.

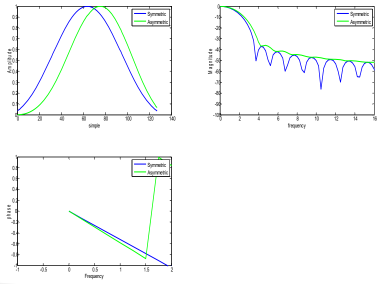

Figure 3: Kaiser-bessel window and A-kaiser-bessel window.

It's assumed that cosine signal is x(t)=Acos($2\pi f_0 t$+θ) and the function of window is w_T, the normalized phase can be obtained by DFT. Two different window functions are added to the same signal (one is symmetric one is asymmetrical), then it can get two different phase values

$$\varphi_1(k-k_0)=\emptyset_1(k)-\theta \quad (1)$$

$$\varphi_2(k-k_0)=\emptyset_2(k)-\theta \quad (2)$$

Where k denotes the frequency bin number in the discrete spectrum and $k_0=f_0/f_\Delta$, f_Δ is frequency resolution. Let (2) subtract (1), the phase difference can get

$$\mu(k)=\Delta\emptyset(k_0)=\emptyset_2(k)-\emptyset_1(k)=\varphi_2(k-k_0)-\varphi_1(k-k_0) \quad (3)$$

Because the phase line of asymmetric window and symmetric window always intersect at the center of main lobe, so there is $\mathrm{u}(k)=0$ when $k=k_0$, that is, the value of normalized frequency is the solution of equation $\mathrm{u}(k)=0$, and the solution of this equation can be approximately obtained by secant method.

3 DISCRETE TIME CLOCK SYNCHRONIZATION

After noise processing, the discrete time clock model can be approximated as a non-noise state

$$t_i(n) = t_i(0) + nT_i \quad (4)$$

Where $t_i(n)$ denotes the time of the n th tick(n=0,1,2…)of the ith clock(i=1,2,…,N, where N is the total number of nodes), T_i is the local periods.

Because of the network topology, the impact of each node on local nodes is different. Therefore, it defined that a_{ij} is the relative strength of the signal received by i from j with respect to the other neighbors of i (there is a normalization condition$\sum_j a_{ij}$=1), and Laplacian matrix can be established according to the connection state of nodes.

$$a_{ij}=\frac{p_{ij}}{\sum_{j\in I_i} p_{ij}} \quad (5)$$

$$\mathbf{L} = \mathbf{I} - \mathrm{A} \quad (6)$$

Where p_{ij} indicates the power received from the j node to the i node, A is an adjacency matrix ($[A]_{ij}$=a_{ij} for $i \neq j$ and $[A]_{ii}$=0), so we have $\mathbf{L}\cdot\mathbf{1} = 0$, where $\mathbf{1}$=[1 1 … 1]$^{\mathrm{T}}$.

Pass through time difference detector of the phase-locked loop, the time information that the local clock node i needs to be coupled can be obtained.

$$\Delta t_i(n) = \sum_{j=1,i\neq j}^{N} a_{ij}\cdot\left(t_j(n) - t_i(n)\right) \quad (7)$$

Then the clock information of the node i is updated by the first order loop filter

$$t_i(n+1) = t_i(n) + T_i + \varepsilon_0 \cdot \sum_{j=1,i\neq j}^{N} a_{ij} \cdot \left(t_j(n) - t_i(n)\right) \quad (8)$$

And the clock information controlled by the Laplacian matrix can be obtained by converting (8) into a vector difference equation.

$$\mathrm{t}(n+1) - t(n) = \boldsymbol{T} - \varepsilon_0\mathbf{L}\cdot t(n) \quad (9)$$

Where the vectors $t(n) = \left(t_1(n) \cdots t_N(n)\right), \boldsymbol{T} = \left(T_1(n)\cdots T_N(n)\right)^T$. Let T_{nom} is the common frequency, so there is

$$\begin{aligned}\mathrm{t}(n) = t(0) + nT_{nom}\cdot\mathbf{1} + n\boldsymbol{T} - nT_{nom}\cdot\mathbf{1} \\ = nT_{nom}\cdot\mathbf{1} + t_0(n)\end{aligned} \quad (10)$$

Plugging (10) in (9), we can get

$$t_0(n+1) - t_0(n) = \Delta\boldsymbol{T} - \varepsilon_0 L\cdot t_0(n) \quad (11)$$

Where $\Delta\boldsymbol{T}$=$\boldsymbol{T} - T_{nom}\cdot\mathbf{1}$, so in the steady-state, there is $t_0(n+1) - t_0(n)$=0, then obtaining the condition

$$\mathbf{L}\cdot t_0(n) = \frac{\Delta\boldsymbol{T}}{\varepsilon_0} \quad (12)$$

There is $\boldsymbol{v}^T\mathbf{L} = 0$, $\boldsymbol{v} = [v_1\ v_2 \cdots v_n]^{\boldsymbol{T}}$ is the left eigenvector corresponding to $\lambda(\mathbf{L}) = 0$. Then the value of common frequency easily follows:

$$T_{nom} = \sum_{i=1}^{N} v_i T_i \quad (13)$$

Moreover, through the further change of variables $z_0(n+1) = t_0(n) - \frac{\mathbf{L}^{+}\Delta\boldsymbol{T}}{\varepsilon_0}$ in (11),we obtain $z_0(n+1) = (\mathbf{I} - \varepsilon_0\mathbf{L})z_0(n)$. since $z_0(n+1)$→$1\boldsymbol{v}^T z_0(1)$,which finally leads to (14)

$$\mathrm{t}(n) \to nT_{nom}\cdot\mathbf{1} + \mathbf{1}\cdot\boldsymbol{v}^T\left(t(0) - \frac{\mathbf{L}^{+}\Delta\boldsymbol{T}}{\varepsilon_0}\right) + \frac{\mathbf{L}^{+}\Delta\boldsymbol{T}}{\varepsilon_0} \quad (14)$$

Finally the neighbor nodes are synchronized, and the system reaches a stable state.

4 NUMERICAL SIMULATIONS

The theoretical signal which is worsened by noise is $x(t)_{e(t)} = x(t) + e(t)$,$e(t)$ is the white noise with zero mean and gauss distribution. It can get the signal to noise ratio (SNR) from -5 to 90 dB through adjusting noise level, the theoretical frequency is set to 256Hz, the sampling frequency is 1024Hz, sample point is 1024 and the phase is $-\pi$. Because of the randomness of noise, the frequency correction results are different in each test, so the root mean square error of the 500 independent experiments is considered.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N_{tr}}\sum_{c=1}^{N_{tr}}(f_c - f_0)^2} \quad (15)$$

Where N_{tr} is test number, f_c is the correction frequency of each test in the case of noise.

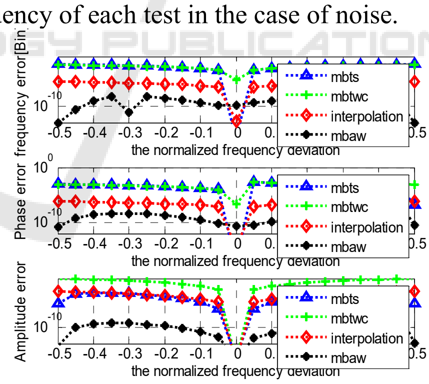

Figure 4: Maximum frequency, phase and amplitude errors for different algorithms.

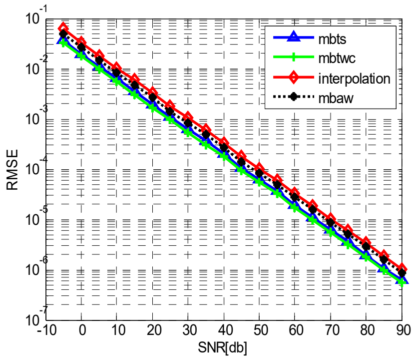

Figure 5: RMSE of 500 independent trials.

From fig.4 and fig.5, it can be seen that the signal processing method of asymmetric window makes the frequency, phase and amplitude errors small enough, and with the increase of SNR, the RMSE gradually decreases, which can reduce the influence of noise.

Here it consider a simple example for N=4, $P_{ij} = 1/d_{ij}$, the common frequency T_{nom} =1, ε_0=0.4, $t(0) = [0.9\ 0.7\ 0.4\ 0.2]^T$.From fig.7. it can be seen that as long as there is a path connection between nodes, the nodes can achieve phase synchronization so that achieve full synchronization and $t_i(n) - nT$ converge to $\sum_{j=1}^{N} v_j t_j(0)$.

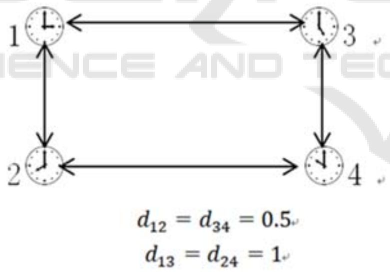

Figure 6: Connection diagram of Network node for N=4

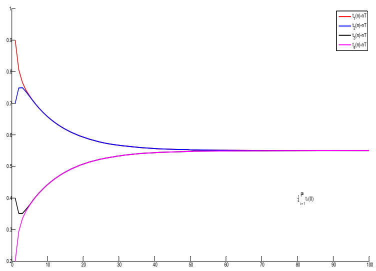

Figure 7: Phases of the N=4 pulse-coupled discrete clocks shown in the box versus period n

5 CONCLUSIONS

This paper proves that combined with the correction of discrete spectrum, the influence of noise in network node's clock can be reduced, and the stable synchronization between nodes clock can be achieved by pulse coupling in physical. The left eigenvector of the Laplacian matrix yields the steady state frequency and phase of the clock.

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