

A Hierarchical Network Synchronization Technique for Asynchronous Broadband Networks

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Abstract—A radio synchronization technique without the use of GPS (Global Positioning System) for OFDM (Orthogonal Frequency Division Multiplexing)-based broadband networks is described. UMTS (Universal Mobile Telecommunications System) has employed three main mechanisms called node, transport channel and radio interface synchronization. The RNC (Radio Network Controller) has been used as a key network component for the centralized synchronization mechanism. Here, we explore a more accurate and simpler asynchronous technique for broadband networks from the perspective of the distributed manner, where MSs (Mobile Stations) play an important role in the timing adjustment. The shadowing effect and the clock drift are taken into account in the mathematical analysis.

I. INTRODUCTION

In general, network synchronization can be divided into a synchronous mode using a reference clock such as a GPS (Global Positioning System) and an asynchronous mode without the use of a GPS. In UMTS (Universal Mobile Telecommunications System) networks, the clock of each RNC (Radio Network Controller) is utilized as a reference for subsidiary Node-Bs [1]. To compensate for clock drift, a synchronous packet is periodically used, which contains a time stamp over the transport bearer [2]. Using the transport and radio interface synchronization methods, frame alignment is accomplished for each MS (Mobile Station) via two Node-Bs w.r.t. an RNC in a centralized manner. However, the wired-line packet transmission between the RNC and the Node-B may lead to a large variation in the delay due to the queueing delay.

In ongoing OFDM (Orthogonal Frequency Division Multiplexing)-based broadband networks, a distributed network architecture without the use of a network controller is extensively employed [3]. The role of Node-B and RNC in UMTS is merged into a network node, termed a BS (Base Station) so that the synchronous method of the UMTS is not directly applicable to this distributed architecture. Since a queueing delay during the wired-line transmission may result in fluctuating synchronization timing, it is necessary to develop a more accurate synchronization technique due to the short duration of OFDM symbols.

This paper explores a radio synchronization technique for asynchronous distributed network architectures. The major contribution is that more accurate synchronization can be achieved due to the absence of a queueing delay during wireless transmission. In addition, the signal flow becomes

simpler and more efficient than that of UMTS due to two node communications (MS to BS) rather than three node communications (MS to Node-B to RNC). In the numerical analysis, the timing adjustment error due to the shadowing effect and the clock drift is derived as a closed form of lognormal distribution over multicell environments with a frequency reuse factor of 1.

II. PROBLEM STATEMENT

In [4], it was demonstrated that the hierarchical master-slave (HMS) synchronization strategy has an advantage of great timing performance and reliability. In 3GPP, a distributed synchronization technique using an MS was proposed in [5], where clock stability was accomplished without the use of HMS synchronization. We present a synchronization technique among BSs with the HMS synchronization structure. This paper describes how to maintain the accuracy of synchronization using feedback signals from MSs after the initial deployment and synchronization alignment.

Suppose that two adjacent BSs (BS1 and BS2) exist over the cellular network under a router. Without loss of generality, let BS1 be the reference BS for synchronization and BS2 be a neighboring BS needed to be synchronized to BS1 throughout this paper. Each MS located in the border area tracks the slot boundary of OFDM symbols delivered from the two BSs. Based on the boundary difference, it estimates a timing offset of BS2 relative to BS1 and sends it to BS2 for clock adjustment.

The procedure described above can be extended to the group of cells. In Fig. 1, BS1 is used as a reference BS for the group. With reference to the clock of BS1, neighboring BSs located in the 1st tier adjust their timing to BS1. The BSs in the 1st

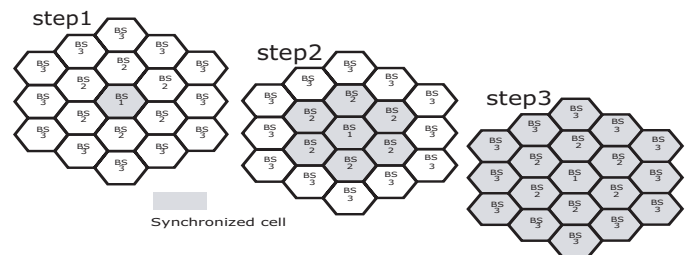


Fig. 1. The synchronization procedure over a multicell environment

tier then become the reference BSs for the 2nd tier, and so on. Finally, all the BSs belonging to the group are synchronized with BS1.

The numerical analysis for the timing adjustment error was performed by three factors. Let Z , T , D and B be random variables. The timing adjustment error (Z) consists of three major components: the radio symbol timing error (T) due to shadowing, the clock drift due to the frequency difference (D) of the crystal [4] and symbol misalignment (B). Then, $Z = T + D + B$ where T , D and B are mutually independent random variables. In addition, T is modeled as a lognormal distribution, D is modeled as a normalized Gaussian distribution and B is obtained by the simulation in [6]. In Section III, the PDFs (Probability Density Functions) are obtained for T , D , B and Z as a function of time.

III. ANALYSIS OF SYNCHRONIZATION TIMING ERROR

A. Candidate Mobile Stations

Let an MS be located at position x in the reference cell (BS1). Then, the path loss from the BS i to the MS is given by

$$L_{(x,i)} = r_{(x,i)}^{-l} 10^{\xi_{(x,i)}/10} = r_{(x,i)}^{-l} \chi_{(x,i)} \quad (1)$$

where l is a path-loss exponent (typically three to four), $r_{(x,i)}$ is the distance from x to the i^{th} BS ($i=1$ for BS1 and $i=2$ for BS2), $\xi_{(x,i)}$ is a Gaussian distributed random variable with zero mean and a standard deviation representing shadowing, and $\chi_{(x,i)}$ is a lognormally distributed random variable. Typically, the standard deviation of ξ is in the range of 6-10 dB for signals from adjacent BSs and 2-2.5 dB for signals from the home BS. The MS then measures the pilot signal difference from BS1 and BS2. If the difference is less than the threshold in (2), the MS sends the clock difference to BS2.

$$\begin{aligned} & P[|\bar{L}_{(x,1)} - \bar{L}_{(x,2)}| \leq \Gamma] \\ &= P[\bar{L}_{(x,1)} - \bar{L}_{(x,2)} \leq \Gamma] \cdot P[L_{(x,1)} \geq L_{(x,2)}] \\ & \quad + P[\bar{L}_{(x,2)} - \bar{L}_{(x,1)} \leq \Gamma] \cdot P[L_{(x,2)} \geq L_{(x,1)}] \end{aligned} \quad (2)$$

where \bar{L} is expressed in dB and Γ is the threshold in dB. Then, (2) can be derived as (3). Let $\xi_e = \xi_1 - \xi_2 = \xi_2 - \xi_1$ where ξ_e is a zero-mean Gaussian random variable with the variance $\sigma_e^2 = \sigma_1^2 + \sigma_2^2$. Thus, (3) is represented as

$$\begin{aligned} & P\left[\xi_e \leq \Gamma + 40 \log\left(\frac{r_1}{r_2}\right)\right] \cdot P\left[\xi_e \geq 40 \log\left(\frac{r_1}{r_2}\right)\right] \\ & + P\left[\xi_e \leq \Gamma + 40 \log\left(\frac{r_2}{r_1}\right)\right] \cdot P\left[\xi_e \geq 40 \log\left(\frac{r_2}{r_1}\right)\right] \end{aligned}$$

$$\begin{aligned} P[|\bar{L}_{(x,1)} - \bar{L}_{(x,2)}| \leq \Gamma] &= P[(\xi_1 - 40 \log r_1) - (\xi_2 - 40 \log r_2) \leq \Gamma] \cdot P\left[r_1^{-4} 10^{\frac{\xi_1}{10}} \geq r_2^{-4} 10^{\frac{\xi_2}{10}}\right] \\ & \quad + P[(\xi_2 - 40 \log r_2) - (\xi_1 - 40 \log r_1) \leq \Gamma] \cdot P\left[r_2^{-4} 10^{\frac{\xi_2}{10}} \geq r_1^{-4} 10^{\frac{\xi_1}{10}}\right] \\ &= P\left[\xi_1 - \xi_2 \leq \Gamma + 40 \log\left(\frac{r_1}{r_2}\right)\right] P\left[\xi_1 - \xi_2 \geq 40 \log\left(\frac{r_1}{r_2}\right)\right] + P\left[\xi_2 - \xi_1 \leq \Gamma + 40 \log\left(\frac{r_2}{r_1}\right)\right] P\left[\xi_2 - \xi_1 \geq 40 \log\left(\frac{r_2}{r_1}\right)\right] \end{aligned} \quad (3)$$

$$\begin{aligned} &= \Phi\left(\frac{\Gamma + 40 \log\left(\frac{r_1}{r_2}\right)}{\sigma_e}\right) \cdot Q\left(\frac{40 \log\left(\frac{r_1}{r_2}\right)}{\sigma_e}\right) \\ & \quad + \Phi\left(\frac{\Gamma + 40 \log\left(\frac{r_2}{r_1}\right)}{\sigma_e}\right) \cdot Q\left(\frac{40 \log\left(\frac{r_2}{r_1}\right)}{\sigma_e}\right) \end{aligned} \quad (4)$$

where $\Phi(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\omega} e^{-\frac{v^2}{2}} dv$ and $Q(\omega) = 1 - \Phi(\omega)$. If MSs are uniformly distributed with $\Gamma = 3\text{dB}$, the percentage of MSs involved in the clock alignment is up to approximately 30% according to (4).

B. Symbol Timing Errors due to shadowing

From (1), the actual distance becomes $r_{(x,i)} = [L_{(x,i)} 10^{-\xi_{(x,i)}/10}]^{-1/l}$. However, the MS does not determine how much shadowing effect is included. Thus, it assumes that the path loss is the average value (i.e., $\xi_{(x,i)}=0$) and the distance is $\hat{r}_{(x,i)} = L_{(x,i)}^{-1/l}$. Since $r_{(x,i)} \neq \hat{r}_{(x,i)}$, the MS miscalculates the distance from the BS. Even though the two BSs are synchronized perfectly, the MS feels that a clock difference between BS1 and BS2 exists by

$$\delta\tau_x = \frac{1}{c} [(\hat{r}_{(x,1)} - \hat{r}_{(x,2)}) - (r_{(x,1)} - r_{(x,2)})] \quad (5)$$

where c is the light velocity. The expected value of (5) is represented as

$$\begin{aligned} E[\delta\tau] &= \int_0^R \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \delta\tau_x(\xi_1 = a_1, \xi_2 = a_2) \\ & \quad \cdot f_{\xi_1}(a_1) \cdot f_{\xi_2}(a_2) \cdot f_X(x) \cdot \Psi_x da_2 da_1 dx \end{aligned} \quad (6)$$

where R is the radius of the cell and Ψ_x is a binary function. Denote A_s as the region where the difference of pilot signal strengths is less than the threshold Γ . Then,

$$\Psi_x = \begin{cases} 1, & \text{if } x \in A_s \\ 0, & \text{otherwise.} \end{cases}$$

The variance of (5) is then obtained by

$$\text{VAR}[\delta\tau] = E[(\delta\tau - E[\delta\tau])^2]. \quad (7)$$

Using the assumption of that the sum of lognormal random variables is also a lognormal random variable, the random variable $\delta\tau$ has a lognormal distribution with the mean in (6) and the variance in (7).

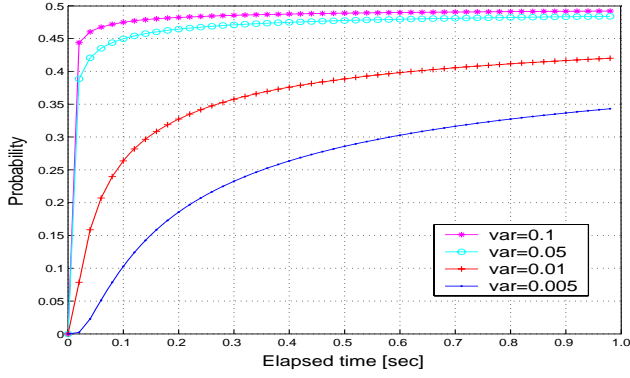


Fig. 2. The probability that the clock drift exceeds $2 \mu\text{s}$ according to the elapsed time

C. Radio Timing Adjustment Error Accumulation

According to the explanation in Section II, the reference cell originally starts from the 0^{th} tier, which becomes a reference cell to the 1^{st} tier cells, which then become reference cells to the 2^{nd} tier cells, and so on. This consecutive timing adjustment should lead to an error accumulation.

The numerical analysis described in Subsection III-B can be extended to an analysis of error accumulation over multicell environments. The sum of symbol timing errors up to the K^{th} tier becomes $\delta\tau_T = \sum_{k=1}^K \delta\tau_k$ where $\delta\tau_k$ is the error of the k^{th} tier relative to the $k^{\text{th}} - 1$ tier. Assume that the PDF at each tier is the same. The expected value is then $m_T = E[\delta\tau_T] = K \cdot E[\delta\tau]$. Since the cell environment is independent, the covariance of $\delta\tau_k$ is 0. The variance of $\delta\tau_T$ then becomes $\sigma_T^2 = \text{VAR}[\delta\tau_T] = K \cdot \text{VAR}[\delta\tau]$. Therefore, the PDF of $\delta\tau_T$ over the multicell environment becomes

$$f_T(t) = \frac{1}{t \cdot \sigma_T \sqrt{2\pi}} e^{-\frac{(\ln t - m_T)^2}{2\sigma_T^2}}. \quad (8)$$

D. The Effect of the Clock Drift

Since each BS uses a physically different clock, the clock drift between two BSs (one is in the i^{th} tier and the other one is in the $(i+1)^{\text{th}}$ tier) is independently determined. Here, we assume that this clock drift error is periodically compensated from the reference cell. Thus, the clock drift between two BSs is only considered. Using the clock model obtained by equation (12) in [7], a Monte-Carlo simulation is performed. From this simulation result, the PDF of the clock drift during a unit time duration Δt is modeled by $D(\Delta t) \sim N(0, \sigma_i^2)$ where N means the normalized Gaussian distribution. Thus, the distribution $D(S\Delta t)$ over the time duration $S\Delta t$ is the sum of i.i.d. random variables. The probability that $D(S\Delta t)$ is larger than a threshold V is given by

$$f_D(S\Delta t) = P\left[D(S\Delta t) > \frac{V}{\sigma_i \sqrt{S\Delta t}}\right] = Q\left(\frac{V}{\sigma_i \sqrt{S\Delta t}}\right).$$

Fig. 2 shows the probability that the BS clock drift exceeds a threshold time $V = 2\mu\text{s}$. Finally, the PDF of the synchronization error Z is given by the convolution of the PDFs of T , D and B , $f_Z(t) = f_T(t) * f_D(S\Delta t) * f_B(t)$.

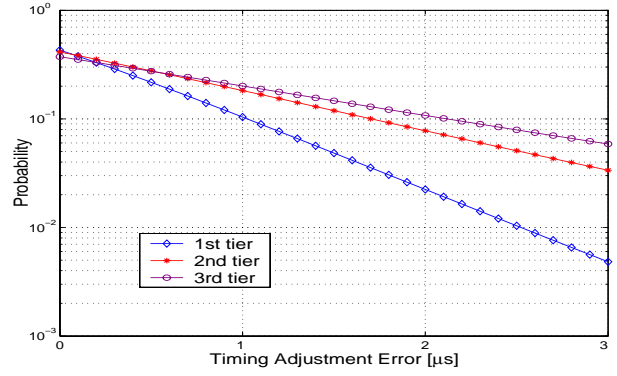


Fig. 3. The PDF of radio timing adjustment error over the multicell environment

IV. SIMULATION RESULTS

Fig. 3 shows the PDF of Z . The threshold Γ is set to 3dB and the deviation of shadowing is set to 2dB at the home cell and 8dB at neighbor cells. It is clear that the symbol timing error increases with the distance from the home BS. As the distance becomes larger, the shadowing variance is increased, and a timing error accumulates. The timing error is around $2.5\mu\text{s}$ with a probability of 0.01 between the reference BS and a neighboring BS. Therefore, MSs can receive OFDM symbols by extending the duration of the cyclic prefix.

V. CONCLUSION

An accurate and simple asynchronous technique for broadband networks over multi-cell environments is presented. In the proposed scheme, the timing adjustment is performed via feedback information from MSs. A numerical analysis for the timing adjustment error can be performed by measuring the radio symbol timing error, the clock drift and the symbol misalignment. This is possible if the timing error is bounded in the range of a few μs .

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