Time synchronization for M-WiMAX femtocells using IEEE 802.11 based wireless backhaul

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Abstract: In this paper, we propose a new time synchronization method for femtocells connected to the core network through IEEE 802.11 based wireless link. In the proposed method, the time information is transmitted to a femtocell via the wireless backhaul using modified IEEE 802.11 beacon frames, and a least squared based estimation method is used to reduce the timing jitter at the femtocell. Through simulations, it is shown that the femtocells using the proposed algorithm satisfy the time accuracy specification for M-WiMAX.

Keywords: femtocell, time synchronization, M-WiMAX, IEEE 802.11

Classification: Science and engineering for electronics

References

1 Introduction

Femtocells, which indicate the personal-use small base stations (BSs), are typically designed for the use in a home or small business [1]. Femtocells have received great attention as a means to enlarge the network coverage as well as increase the network capacity, especially indoors. Since a femtocell is connected to the cellular core network through an existing broadband Internet connection, it often requires a complicated construction to install a new Internet link due to the lack or insufficient capacity of existing Internet connection. In this case, an attractive alternative is the use of wireless backhaul like Wi-Fi which connects a femtocell to the core network through a wireless link [2].

When macrocells and femtocells coexist, the Mobile WiMAX (M-WiMAX) system requires time synchronization between network equipments including the core network, macro BSs, BS controllers, and femto BSs [3]. In general, macro BSs acquire the reference time information through the global positioning system (GPS). Femto BSs, by contrast, hardly use the GPS, because of the difficulty of receiving the GPS signal inside buildings and the rise in cost. Instead, a macro BS aided synchronization method was considered which extracts the time information from the preamble of the macro BS [4]. However, this method makes it difficult to extend the network coverage by restricting the femtocell location within the coverage of macro BSs. As an alternative, synchronization algorithms based on IEEE 1588 and IEEE 802.1AS were proposed in [5, 6], yet these approaches require an additional cost for implementation of synchronization protocols.

In this paper, we propose a new time synchronization method for M-WiMAX femtocells which have Wi-Fi capability for wireless backhaul connection. In the proposed scheme, the Wi-Fi access point (AP) connected to the core network transmits beacon frames to Wi-Fi access terminals (ATs) connected to femto BSs, and the time information recovered from the beacon frames is shared with femto BSs. To reduce the time jitter, we slightly modify the IEEE 802.11 beacon frame format and derive an adaptive time estimation method. Simulation results show that the proposed scheme performs better than existing IEEE 802.11 synchronization techniques, and demonstrate that the time information recovered by the proposed algorithm satisfies the M-WiMAX requirements for time accuracy.
2 Proposed beacon frame format

In the IEEE 802.11 standard, an AP periodically sends a beacon frame to nearby ATs to announce the system parameters including the clock timestamp, according to the predetermined beacon interval [7]. When a data frame uses the channel at the time of beacon transmission, the transmission of a beacon frame is delayed due to carrier sense multiple access with collision avoidance (CSMA/CA) operations. This CSMA/CA deferral causes some mismatch between the timestamp included in a beacon frame and the actual beacon transmission time. The IEEE 802.11 standard demands that the AP sets the timestamp considering the scheduling delay as well as the processing delay in the physical layer (PHY), yet the residual time error still reaches up to $\pm 4 \mu s$ [8]. In M-WiMAX, the time error shall be less than $\pm 2 \mu s$ when the handover between the macro BS and the femto BS is supported [3]. Thus the residual time error needs to be further reduced.

The transmit time of a beacon frame can be accurately measured after the transmission is complete. Therefore, we propose a new beacon frame format that includes an additional field to denote the actual transmit time of a prior beacon frame. The overhead increase by the new field can be minimized by transmitting the time difference between the timestamp and the actual beacon transmit time. For example, the beacon frame transmitted at the $n$th beacon interval contains the field indicating the time difference between the $n$th timestamp and the actual beacon transmit time of the $(n-1)$th beacon frame.

3 Proposed time estimation algorithm

Fig. 1 shows the transmission model for beacon frames from the AP to the AT. A beacon frame generated in the AP suffers from the scheduling delay $D_{MAC,AP}$ and the processing delay $D_{PHY,AP}$ in MAC and PHY, respectively. Similarly, a beacon frame is delayed in the AT MAC and PHY by $D_{MAC,AT}$ and $D_{PHY,AT}$, respectively. Also, the propagation delay $D_{air}$ is added between the transmit and receive antennas. According to the IEEE 802.11 standard, $D_{PHY,AP}$ and $D_{PHY,AT}$ are separately adjusted at the AP and the AT. Also, $D_{MAC,AP}$ can be corrected by using the proposed beacon format in Section 2. Note that a residual time error up to $\pm 0.5 \mu s$ still remains in the proposed beacon format due to the finite timer resolution of $1 \mu s$.

At the transmitter, the actual transmit time of the $n$th beacon frame,
s(n), is expressed as
\[ s(n) = t(n) + u(n) \]  
(1)
where \( t(n) \) is the value of the timestamp included in the \( n \)th beacon frame and \( u(n) \) means the residual time error between the timestamp and the actual transmit time. Then, the receive time of the \( n \)th beacon frame in the AT MAC is denoted as
\[ r(n) = x(n) + v(n). \]  
(2)
Here, \( x(n) \) and \( v(n) \) are defined by
\[
\begin{align*}
x(n) &= t(n) + D_{PHY,AT} \\
v(n) &= u(n) + D_{air} + D_{MAC,AT}(n).
\end{align*}
\]
(3)–(4)
In (2)–(4), \( x(n) \) is simply computed at the AT by using the received timestamp \( t(n) \) and the constant delay \( D_{PHY,AT} \), whereas \( v(n) \) is a random noise which is not known at the AT. In (2), \( r(n) \) is the receive time measured by the AP timer. Practically, the receive time is measured by the local timer of the AT. Suppose that \( y(n) \) denotes the receive time of the \( n \)th beacon frame measured by the AT timer. Then, \( y(n) \) is given by
\[ y(n) = c_1 r(n) + c_2 \]  
(5)
where \( c_1 \) is the AT clock frequency over the AP clock frequency, and \( c_2 \) indicates the clock phase offset between the AT and AP. Substituting (2) in (5), we get
\[ y(n) = c_1 x(n) + c_2 + w(n) \]  
(6)
where \( w(n) = c_1 v(n) \). Suppose that the AT has received \( N \) beacon frames from \( n = 0 \). By extending (6), the receive time of \( N \) beacon frames is expressed as
\[ y = Xc + w \]  
(7)
where \( y = [y(0), y(1), \cdots, y(N - 1)]^T \); \( c = [c_1, c_2]^T \); \( w = [w(0), w(1), \cdots, w(N - 1)]^T \); and the matrix \( X \) is defined by
\[ X = \begin{bmatrix} x(0) & x(1) & \cdots & x(N - 1) \\ 1 & 1 & \cdots & 1 \end{bmatrix}^T. \]  
(8)
Assume that \( w(n) \) is an independent and identically distributed (i.i.d.) white noise. Then, the coefficients \( c_1 \) and \( c_2 \) can be estimated in the least squares (LS) sense as follows.
\[ \hat{c} = (X^TX)^{-1}X^Ty \]  
(9)
where \( (\cdot)^T \) means the transpose operation. Using \( \hat{c} \) in (9), the receive time measured by the AT timer is adjusted by
\[ \hat{y} = X\hat{c} \]  
(10)
where \( \hat{y} \) is the corrected receive time. Moreover, the time error between the AT and AP timers is given by

\[
e = X\hat{c} - Xc = X \left( X^T X \right)^{-1} X^T w.
\]

(11)

From (11), the mean square error (MSE), \( J \), is computed as

\[
J = \frac{1}{N} E \left[ tr(\mathbf{e} \mathbf{e}^T) \right] = \mu_w^2 + \frac{2\sigma_w^2}{N}
\]

(12)

where \( E[\cdot] \) denotes the expectation; \( tr(\cdot) \) means the trace operation; \( \mu_w = E[w(n)] \approx D_{\text{air}} \); and \( \sigma_w^2 \) is the variance of \( w(n) \). Note that the MSE in (12) decreases as the number of beacon frames increases.

The LS method requires the computation of (9) at every reception of a beacon frame. To reduce the computational load, we derive an adaptive estimation algorithm based on the recursive least squares (RLS) approach in pp. 562–588 of [9]. In the exponentially weighted LS method, we minimize the cost function

\[
J(n) = \sum_{k=0}^{n} \lambda^{n-k} |y(k) - c^T(n)x(k)|^2
\]

(13)

where the coefficient vector \( c(n) \) is defined by \( c(n) = [c_1(n), c_2(n)]^T \); the filter input vector \( x(n) \) is given by \( x(n) = [x(n), 1]^T \); and \( \lambda \) is the forgetting factor which is a positive constant close to 1. By differentiating \( J(n) \) with respect to \( c(n) \), the coefficient vector \( c(n) \) minimizing \( J(n) \) is obtained by

\[
c(n) = \Phi^{-1}(n)z(n)
\]

(14)

where \( \Phi(n) \) and \( z(n) \) are defined by

\[
\Phi(n) = \lambda \Phi(n-1) + x(n)x^T(n)
\]

(15)

\[
z(n) = \lambda z(n-1) + x(n)y(n).
\]

(16)

Using (14)–(16), the RLS algorithm computing \( c(n) \) is derived as follows.

\[
k(n) = \lambda^{-1} \Phi^{-1}(n-1)x(n)/(1 + \lambda^{-1}x^T(n)\Phi^{-1}(n-1)x(n))
\]

(17)

\[
c(n) = c(n-1) + k(n)(y(n) - c^T(n-1)x(n))
\]

(18)

\[
\Phi^{-1}(n) = \lambda^{-1} \Phi^{-1}(n-1) - \lambda^{-1}k(n)x^T(n)\Phi^{-1}(n-1)
\]

(19)

Here, \( c(0) = 0 \) and \( \Phi^{-1}(0) = \delta^{-1}I \) where \( \delta \) is a a small positive constant.

### 4 Simulation results

The performance of the proposed method is evaluated through simulations for M-WiMAX femtocells using 802.11 based Wi-Fi backhaul. In the Wi-Fi AP and AT, the following parameters were assumed: the beacon interval was 100 ms; the time slot was 9 \( \mu s \); the initial phase offset of the AT timer was 200 \( \mu s \); \( u(n) \) in (1) was uniformly distributed in the range of \( \pm 4 \mu s \) in the 802.11 beacon format and \( \pm 0.5 \mu s \) in the proposed beacon format, respectively; \( D_{\text{air}} \) was 0.33 \( \mu s \) (the distance was 100 m); \( D_{\text{MAC,AT}}(n) \) was uniformly distributed in the range of \( \pm 4.5 \mu s \).
we used $\delta=0.01$ and $\lambda=0.999$, and the maximum time jitter was defined by three times the standard deviation of the time estimation error. We used the IEEE 802.11 beacon format and the proposed beacon format in the AP side, while employing the 802.11 time correction method [7] and the proposed RLS time estimator in the AT side. So, four time synchronization scenarios were considered. Every value of the simulation results were obtained by averaging more than 100 independent realizations.

Fig. 2 compares the time jitter performance, when the AT timer has no clock frequency offset ($c_1=1$ in (5)). Since the AT timer is updated by using the timestamp of the latest beacon frame in the 802.11 time correction method, the maximum time jitter remained constant without regard to the received number of beacon frames. The proposed RLS algorithm reduces the time error via time-averaging, thus the maximum time jitter decreased as the number of beacon frames increased. When the 802.11 beacon format and the RLS algorithm were used, the maximum time jitter satisfied the M-WiMAX specification in 150 beacon intervals. When the proposed beacon format and the RLS algorithm were used, the convergence speed was improved and the maximum time jitter was reduced below the specification in only 90 beacon intervals.

In Fig. 3, the steady-state jitter performance is compared, when the clock frequency offset increases. Whereas the 802.11 time correction method simply adjusts the phase offset caused by the frequency offset at every beacon interval, the proposed RLS method compensates for the phase offset as well as the frequency offset within beacon intervals. Therefore, the time jitter of the RLS estimation scheme was not affected by the frequency offset, while the time jitter of the 802.11 time correction method linearly increased with the frequency offset. Overall, the proposed RLS algorithm satisfied the M-WiMAX jitter specification without regard to the frequency offset.
5 Conclusion

This paper presents a new time synchronization method for femtocells using IEEE 802.11 based wireless backhaul. Simulation results demonstrate the benefits of the proposed method compared to the existing scheme in terms of the time jitter. The proposed approach can be applied to femtocells for other cellular networks such as IEEE 802.16m and CDMA 1xEV-DO.

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