A synchronization scheme for the Wireless Channel-oriented Ad-hoc Multi-hop Broadband system (W-CHAMB)

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ABSTRACT

W-CHAMB (Wireless Channel-oriented Ad-hoc Multi-hop Broadband) is an innovative MAC scheme for beyond 3G wireless systems. It can operate under multi-hop and ad-hoc environment and is able to provide QoS (Quality of service) guarantee. The basic ideas of the scheme are using energy signals to contend in order to get the access right and transmitting data by means of periodic time slots (TDMA channels). However, synchronization is a headache issue for distributed TDMA systems. This paper introduces a solution for the problem. A modification of the MAC frame structure introduced in former publications enables to implement the synchronization function. The system is easily configured to support wireless nodes up to 3000 for one-hop ad-hoc network and the extended algorithm could support multi-hop scenarios. An event driven stochastic simulator has been developed to verify the ideas. The proposed scheme can also be used to solve the synchronization issue for other TDMA systems with distributed control, like wired TDMA distributed systems.

1. INTRODUCTION

Researches for beyond 3G wireless broadband systems are hotly underway all over the world. Lots of new ideas have been put forward. Definitely, QoS guarantee, multi-hop and ad-hoc will play important role in future wireless broadband systems. W-CHAMB is the one proposed concept that substantially differs from the well-known IEEE 802.11. Performance evaluation results published earlier have shown many superiorities of this proposed wireless system [2, 3, 4, 19]. The MAC protocol of W-CHAMB is based on TDMA channels that are established between adjacent stations and energy signals are used to contend for the access right. As different combination of access signals can be looked as different grades, access contentions are correspondingly designed according to QoS requirement. Therefore implementation of QoS is easily achieved without increasing too much overhead. Meantime, with the introduction of Busy-E-Signal, hidden station problem is greatly reduced, which makes W-CHAMB very suitable to operate in multi-hop and ad-hoc environments. However, the goal of the system that is able to operate under fully distributed scenario makes the implementation of time synchronization for the system pretty difficult.

Though Global Positioning System (GPS) provides an easy way to get an accurate time base, it can't be taken as a synchronization solution for distributed system due to its requirement of line of sight to the GPS satellites and its high power consumption.

Lots of synchronization algorithms for distributed network systems have been put up over years. Network Time Protocol (NTP) [10] is in use to synchronize clocks and coordinate time distribution in the internet world. In order to provide time synchronization for newly emerging sensor networks, RBS (Reference-Broadcast Synchronization) [12], based on reference broadcast, is introduced to get higher time precision. The IEEE 802.11 standard [13], the widely used wireless LAN (WLAN) standard, has its own synchronization mechanisms to support both BSS (basic service set) and IBSS (independent basic service set). BSS is called infrastructure mode in which communications take place between the access point and wireless nodes, while IBSS is the ad-Hoc mode in which communications happen between wireless nodes in a self-organized network. The scalability problem analysis of the synchronization algorithm for IEEE 802.11 IBBS and an enhanced scheme can be found in [9].

Although lots of difference exists among those distributed schemes, they share the same essential idea: nodes periodically send out time messages to their neighbours, and the recipients use the received messages to calculate their own time reference by means of various evaluation algorithms. All of the above algorithms are based on packet-oriented MAC schemes, like IEEE 802.3 or IEEE 802.11. Some of them can be extended to support multi-hop operation.

The TDMA-based W-CHAMB network can be viewed as a channel-oriented technology. A CAC (call admission control) algorithm on the top of MAC layer decides the number of time slots allocated for a channel. The algorithms introduced in this paper are meant to solve the synchronization issue for the W-CHAMB system. The basic idea of the synchronization algorithm takes the same way as other schemes: nodes send Beacons periodically and the recipients get time information from analysing the Beacons. With a modification of MAC frame structure introduced in earlier publications, the proposed scheme can support wireless nodes up to 3000 in one hop while providing a highly accurate time reference. This algorithm can be easily extended to support multi-hop operation.

The remaining parts of this paper are organized as follows: In Section 2, we shortly review the W-CHAMB system. In Section 3, the algorithm is described, including the Basic algorithm (§3.1), its mathematical analysis (§3.2) and an extended algorithm to support multi-hop (§3.3). Simulation works are presented In Section 4. Section 5 concludes the paper.

2. W-CHAMB

Ad-hoc and multi-hop networking, due to their ability to be quickly deployed and self-organized, has been a topic of great interest in wireless communication community for many years. Currently, most research works about ad-hoc and multi-hop use IEEE802.11 [13, 14] or Bluetooth [6] as their MAC scheme. Some research results have shown that IEEE802.11 does not work well in multi-hop wireless networks because of the fact the interference range is not same as the communication range [8]. Furthermore, IEEE802.11 can't work efficiently when supporting real-time services. On the contrary, Bluetooth can perform ad-hoc and multi-hop operation well with QoS guarantee. But Bluetooth only offers a link rate of 1Mbps per link (maximum 721kbps user data), and its Inquiry procedures cause long periods of network partition [5].

The W-CHAMB system [2, 3, 4, 19] is designed to be able to operate under distributed control with QoS guarantee. Nodes in W-CHAMB are using energy signals to contend for a TDMA channel in order to get the access right and transmit data by means of periodic time slots (TDMA channels). Energy signals transmitted in an ECH slot are used to signal the occupancy of corresponding TCH in order to eliminate the hidden station problem.

The MAC frame and waveform of energy signals are shown in Figure 1 and Figure 2 respectively.

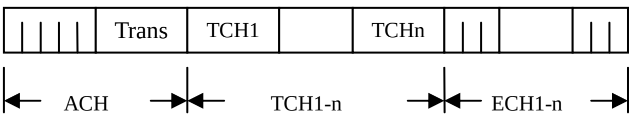

Figure 1: MAC frame structure of W-CHAMB

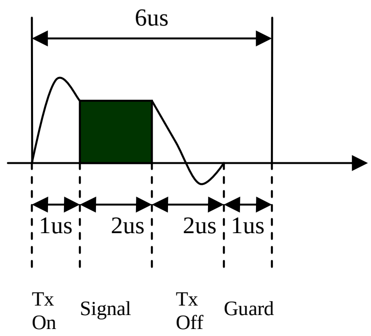

Figure 2: Waveform of energy signal

A MAC frame is composed of three phases: Access channel (ACH), transmission channel (TCH) and Echo channel (ECH) phase. The ACH is used to contend access among wireless nodes nearby. The TCHs transmit user data. The ECHs are employed to signal by the received station the occupancy of corresponding TCHs. An ACH comprises an ACH-Contention sub-phase and an ACH-Trans sub-phase. An ACC-Contention contains m energy signals allowing for 2^m different signals, each associated with a QoS level. ACH-Trans sub-phase carries the access protocol data unit. The frame length can be expressed as:

$$T = 6us * m + Ta\_trans + Ttch * n + 6us * n \quad (1)$$

Where m represents the number of ACH energy signals, n represents the number of TCH. $T_{a\text{-}trans}$ is the duration of ACH-Trans and T_{tch} is the duration of one TCH slot.

The mechanism of ACH is as follows:

1. Before contending, each node generates a number ranging from 0 to 2^m according to its QoS requirement.
2. A wireless node checks the generated number bit by bit, when the bit is 1 it sends an energy signal, for 0 it listens. The most significant number is transmitted first.
3. During a listening period, once a contending wireless node hears an energy signal, it loses the right to continue contention. The node must cancel the rest of its pending energy signals and attempt to contend again later. During ACH-Contention, if a node senses nothing, it means that the node has won the contention and is able to use ACH-Trans to send out an access packet.

Currently W-CHAMB is designed to operate at 5.2 GHz adopting the IEEE 802.11a modem with transmission rates ranging from 6Mbps (BPSK) to 54Mbps (64QAM).

The signal strength at the receiver is

$$P_R = P_T \bullet G_T \bullet G_R \bullet \left(\frac{\lambda}{4\pi} \right)^2 \bullet \frac{1}{d^{\gamma}} \quad (2)$$

In formula (2) P_T represent the radiated power of transmitter and P_R the input power of the receiver. G_T and G_R stand for antenna gains. λ is the wavelength and d is the distance between sender and receiver [1]. From formula (2), we can get

$$d = \frac{10\log^{P_T} + 10\log^{Ge \bullet Gt} - 10\log^{P_R} + 20\log(\frac{c}{4 f\pi})}{10 \bullet \gamma} \quad (3)$$

As it can be seen from formula (3), different working frequencies have different transmission ranges. Assuming P_T=160mW, antenna gain is equal to 6dbi, attenuation factor γ =2.6, minimal receiver sensitivity level is -82dbm when the most robust modulation way BPSK1/2 is adopted [7, 18], we can get from (3), for 5.2 GHz, d_{max}=300m, and for 2.4 GHz, d_{max}=520m. Therefore maximal signal propagation delay under 5.2 GHz is 1us, while it is 1.73us under 2.4 GHz. This value is highly associated with the design of the energy signal length. Synchronization schemes described later assumes the range and delay calculated for 5.2 GHz.

3. The Synchronization algorithm for W-CHAMB

First the scheme for an one-hop ad-hoc network, called the basic algorithm and a mathematical analysis of basic algorithm will be introduced. Second we present synchronization means to support multi-hop.

3.1 The basic algorithm

The MAC frame structure shown in Figure 1 has an obvious shortcoming. As QoS levels are normally no more than 20, the number of energy signals in ACH is no more than 5 (2^5=32>20). Using such few choices to contend for a channel would result in lot of collisions even in small-scale network.

We add a sub-phase named Contention phase in ACH, which also consists of several energy signals. The number of the energy signals may be adjusted according to number of the wireless nodes. The purpose of the sub-phase is to greatly reduce the collision probability.

Let g be the number of energy signals in Contention phase. The MAC frame is changed from Eq. (1) to Eq. (4) shown below:

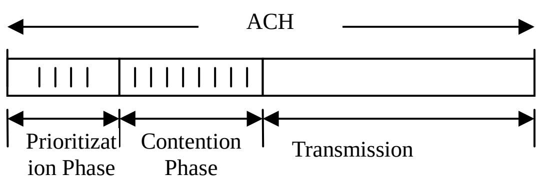

Figure 3: Modified ACH structure

$$T = 6us * (m + g) + Ta\_trans + Ttch * n + 6us * n \quad (4)$$

Now the access procedure described before should read:

1. Nodes use a QoS-related number to contend for access in prioritization phase by means of sending and listening scheme.
2. Nodes surviving the first phase randomly generate a number between 0 and 2^g according to an uniform distribution. Nodes then use this number to contend for access in the contention phase by means of sending and listening scheme.
3. The nodes winning both the prioritization and contention phases have the right to transmit data in the subsequent ACH-Trans sub-phase.

Parameter	Value
m	4
g	8
$T_{a\text{-}trans}$	28us
T_{tch}	45us
n	16

Table 1: One possible parameters setting for MAC frame

Though this change introduces additional overhead, the benefit is pretty obvious. For instance, taking parameters in Table 1, we can calculate an increased overhead of:

$$\frac{g \times 6us}{T - g \times 6us} = \frac{8 \times 6us}{916us - 8 \times 6us} = 5.5\% \quad (5)$$

But the probability of collision is minimized to $1/2^g$=1/256 in comparison to 1/32.

After introducing to Contention phase, the following synchronization algorithm becomes possible due to substantial reduction of collision probability. Firstly we present the basic algorithm. “Basic” here means all transmissions happen in an one-hop ad-Hoc network, i.e. the network operates in self-organized mode and each node is in the transmission range of all the others.

The Beacon frame, a terminology can also be found in other synchronization schemes, is specified here to contain time information and the network ID. Its main function is to exchange time information among the wireless nodes nearby.

In order to achieve synchronization, all the nodes in a network participate in the process as described in the finite state machine shown in Figure 4.

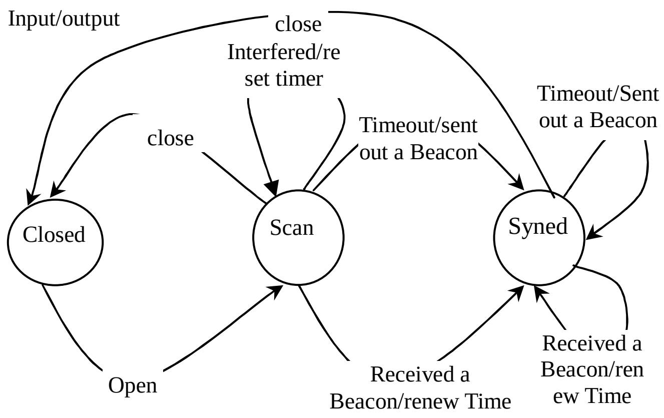

Figure 4: Synchronization Finite state machine for one-hop Ad-Hoc network

1. After switching on a node, the state of the node is switched from Closed to Scan and start a timer. In Scan state, if the node can receive a Beacon before timeout, it renews the local time, cancels the timer and enters in Syned state. If no signal is received before the timer is out, the node generates a Beacon based on its own information, contends to broadcast through the ACH. When succeeding, it then enters in Syned state, else, it resets the timer. In case of the node senses interference or senses energy signals before timeout, it has to reset the timer and stay in Scan state.
2. In Syned state, immediately after a node received a valid Beacon or has sent out a Beacon by itself, the node generates a random number uniformly distributed in the range between s (s>1) and s+w (w>0). Then the node uses the number to set a timer. If a valid Beacon is received before timeout, it renews the local time by analysing the Beacon, cancels the timer and regenerates a timer as described. When the timer expires, the node creates a Beacon based on its own information, sends it out either through a TCH being used by this node or ACH if no TCH being used by this node.

The reason for setting the timer in Syned state from s to s+w rather than from 0 to s+w is because we aim not to introduce too much overhead. And this setting also leads to power-saving. Anyway high time precision is still achieved.

When a node wishes to broadcast a Beacon by means of contending in ACH, the number used in the prioritization phase is also generated according to a uniform distribution. It means when a node wishes to send out a Beacon, the number that is used to contend ranges from 0 to 2^{m+g}. If we use the parameters specified in Table 1, the number ranges from 0 to 2^{12} =4096. With such a big range, it can be said that there is always a winner in almost each contention situation. Therefore Beacon frames can be found on air in time, which is very important to implement synchronization and get high accuracy. The detailed mathematical analysis will be given in the following part.

Let T_R be the timestamp of the received Beacon and T_L be the local timestamp. Assuming s=8 and w=4, the principle of renewing local timestamp when receiving a beacon is given as follows:

1. If $T_R < T_L$ or If $T_R - T_L > 2us$, do nothing.
2. If $0 < T_R - T_L < 2us$, use Eq. 6 to renew

$$T_L = T_L + \frac{T_R - T_L}{2} \qquad 0 < T_R - T_L < 2us \tag{6}$$

3.2 Mathematical analysis of basic algorithm

This part presents an analytical performance evaluation of the basic synchronization algorithm. Firstly we will examine the behaviour of Beacon broadcast. Then we will analyze whether the algorithm meets the time requirement of the system.

At first definitions are given:

Let p(n,b,w) denote the probability that one node of an one-hop ad-hoc network with a number of n nodes , succeeds in beacon broadcast over the ACH. Here b is the sum of m and g.

Let p'(N,b) be the probability that one node succeeds in ACH contending when N wireless nodes contend simultaneously. The b is the sum of m and g.

Let p(L=l) and p(L<l) be the probability that the number l is uniformly generated from interval 0 to 2^b and the probability that the numbers below l are uniformly generated from 0 and 2^b respectively.

Obviously, p'(N,b) can be expressed as:

$$p'(N,b) = \binom{N}{1} \sum_{l=1}^{2^b} p(L=l) \bullet (p(L<l))^{N-1} \tag{7}$$

As in Syned state a Beacon is generated in the period [s,s+w], that means only n/w nodes will contend at the same moment in the future. So we can get (with n>w):

$$p(n,b,w) = \binom{n/w}{1} \sum_{l=1}^{2^b} p(L=l) \bullet (p(L<l))^{\frac{n}{w}-1} \tag{8}$$

From the definition, p(L=l) and p(L<l) can be calculated:

$$p(L=l) = \frac{1}{2^b} \tag{9}$$

$$p(L<l) = \frac{l-1}{2^b} \tag{10}$$

So that:

$$p(n,b,w) = \frac{n}{w} \sum_{l=1}^{2^b} \frac{1}{2^b} \bullet (\frac{l-1}{2^b})^{\frac{n}{w}-1} \qquad n > w \tag{11}$$

According to Eq. (11), Figure 5 and Figure 6 show the relationship between the number of wireless nodes and the success probability p(n,b,w). From the Figure 5, it can be seen even with w=1, if b is set to 12, that a Beacon can be successfully sent out with the probability of 0.9 when the number of nodes is 1000 or with the probability of 0.73 when the number of nodes is 3000. And if we let w take effect, saying w=4, the effect is more obvious. As Figure 6 reveals, when w=4 and with b=12, a Beacon can be successfully sent out with the probability of more than 0.9 in the large-scale network with 3000 nodes.

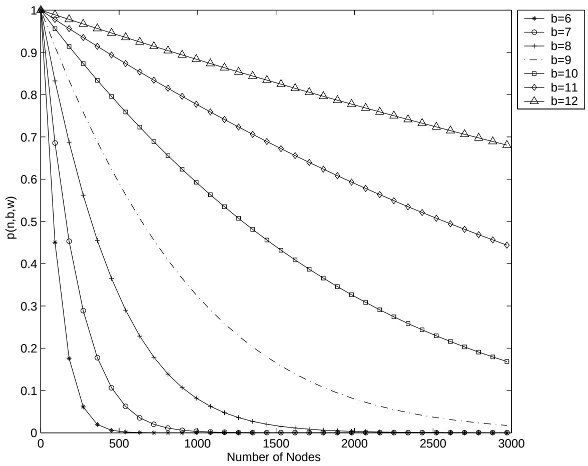

Figure 5: p(n,b,w) with w=1

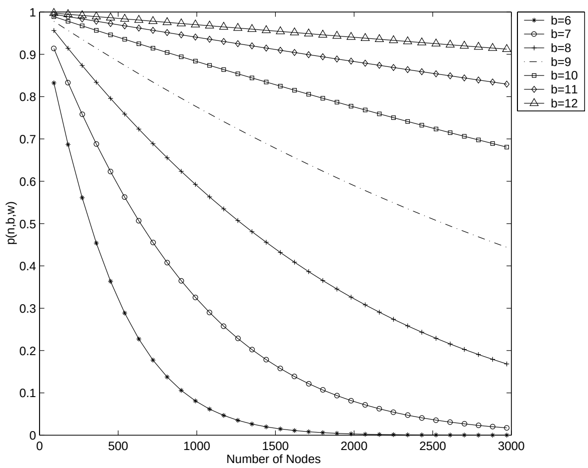

Figure 6: p(n,b,w) with w=4

Actually it's meaningless to support an one-hop ad-hoc network with nodes of more than 500. From the synchronization's point of view, that the number of energy signals in ACH is 12, which is far enough. However besides the Beacon frame, another kind of control frame named RCC-Setup (RCC means real channel connection), in which QoS requirement is carried, should be broadcasted out when contending for the ACH. The number of energy signals of the Contention phase in the ACH must be kept high enough in order to minimize collisions when transmitting RCC-Setup frames.

As mentioned in section 3.1, in Snyed state, after receiving or sending out a Beacon, a node generates a delay timer between [s,s+w]. If no Beacon is received during the period, the node will send out a beacon. That means the refresh time period is between [s*T, (s+w)*T]. Here T represents the MAC frame length. TDMA systems are time-sensitive. Now let's examine whether the proposed scheme meets the minimal requirement of time precision.

1. As mentioned in section 2, for 5.2G OFDM technology, the largest transmission range under consideration is 300m. Therefore the maximal transmission delay is 1us.
2. Typical crystal oscillators are accurate on the order of one part in 10e+4 to 10e+6 [11], so it can be calculated that two nodes' clocks will drift 1-100us per second. Given s=8, w=4 and T=916us (from Table 1), the maximal allowed drift time caused by oscillators is 1us.
3. Analyzing the MAC frame, it can be found that the most time sensitive part appears in the energy signals contention over the ACH. From the waveform of the energy signal, we can deduce that maximal tolerable time difference between the received energy signal and local energy signal is between [-1us,3us].

From points 1 and 2, it can be seen that the maximal time difference between the received signals or packets and local's is in the range of [-1us, 2us], which falls into the maximal tolerable time difference. That means the synchronization algorithm can be expected to work well.

3.3 Extended algorithms for multi-hop

Firstly, in order to support multi-hop, wireless nodes are divided into 4 types:

- ✧ WR_1--Wireless routers with the ability to initiate a network
- ✧ WR_2--Wireless routers without the ability to initiate a network
- ✧ WM_1--Wireless nodes with the ability to initiate a network
- ✧ WM_2--Wireless nodes without the ability to initiate a network

Figure 7 shows the finite state machine (FSM) for a multi-hop scenario. In the chart, only nodes of type WM_1 and WM_2 are involved. Compared to the FSM for an one-hop scenario, a state named 'Interfered' is added. Special attention should be paid on state transition No.4: this state transition only applies to nodes of type WM_1s.

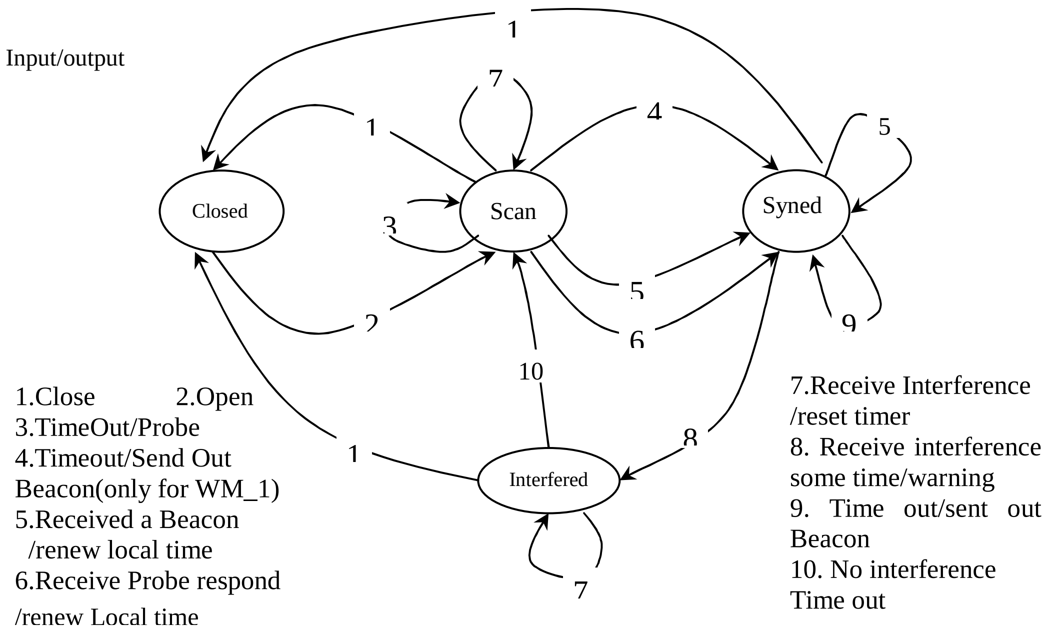

Figure 7: Finite state machine for multi-hop network synchronization

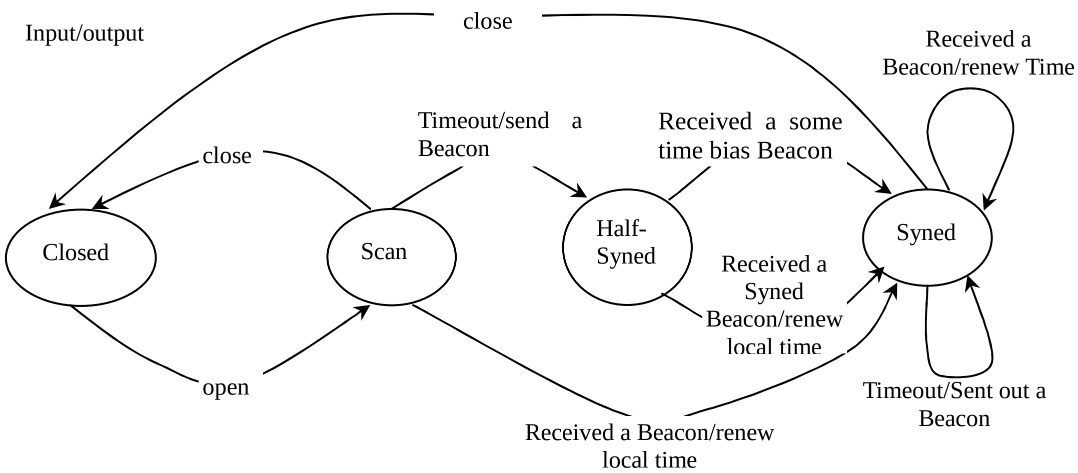

Figure 8: Finite state machine for WM_1 in multi-hop scenario

The algorithm for Multi-hop network synchronization must take into consideration that any nodes of one ad-hoc network don't interfere with other ad-hoc network nodes. If a node can receive signal from different networks with different time references, the node should switch its state from 'Syned' to 'Interfered', in which state the node only have right to listen but can't send. Only after the node makes sure that there is no interference any more, it can restart its synchronization procedure again.

In order to deploy a multi-hop network into a wide area quickly, a special synchronization algorithm for the type of WR_1 is developed. The corresponding FSM is shown in Figure 8. This algorithm can be used in some topologies as shown in Figure 9-11. After synchronization has been built up between those 'powerful' wireless nodes, the other kinds of wireless nodes can start to work by means of listening at first and then joining a network.

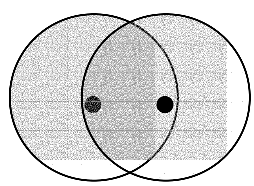

Figure 9: Two WR_1s' deployment

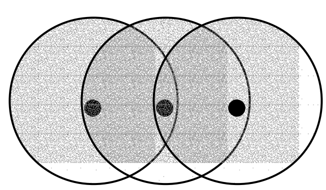

Figure 10: Three WR_1s' deployment

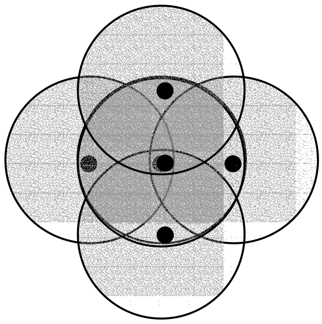

Figure 11: Five WR_1s' deployment

Pictures shown in Figure 9-11 are very ideal topologies. The node pattern however match those proposed for the introduction of relay based wireless broadband system [20].In real world, due to some factors like the different transmission power of WR_1s and shadowing obstacles between nodes, the transmission range might be irregular. However in the above scenarios, as long as at most two WR_1s are in the transmission range of each other (of course interference ranges spread much more widely), the designed mechanism takes effect.

Normally both WR_1s and WR_2s have adequate power supply. So they are configured with higher transmitting power than those of WM_1s and WM_2s. To save the power of average nodes and let multi-hop network be more stable, wireless routers should take more responsibility to send out Beacons. Due to the flexibility of the ACH, we can let wireless routers generate higher random numbers in the prioritization sub phase and reduce the value of w, which can lead wireless routers to have higher probability to send out a Beacon.

4. Simulation works

To verify the synchronization model and evaluate multi-hop performance of W-CHAMB, an event-driven simulator has been developed based on SPEETCL (SDL Performance Evaluation Tool Class Library) [17] in C++. In order to examine the performance for an indoor scenario, a Multi-Wall-and-Floor Model is adopted as indoor path loss Model. For the OFDM-based physical layer, packet errors are calculated according to relationship between C/I and packet error ratio for fixed length packets provided by [15]. For transmitter and receiver, we get the critical values like transmission power and receiver sensitivity from published OFDM-related standards like IEEE 802.11a [18] and HiperLan/2 [7].

Some scenarios have been examined. All the above introduced algorithms have shown to work well so far in the simulator. The detailed simulation results will be presented in the near future.

5. Conclusions

In this paper, we introduced a synchronization algorithm for W-CHAMB system. With modification of the MAC frame structure, the proposed synchronization scheme becomes possible. A related mathematical analysis for basic algorithm has been conducted and shows this algorithm can be used to support large-scale one-hop ad-hoc networks with the number of nodes up to 3000 or even more. The extended algorithms are presented to support multi-hop. An event-driven simulator has been developed and is used to examine the proposed ideas. So far all the algorithms work well in simulator. The detailed simulation results will appear in our future paper. The developed basic algorithm can be used as synchronization scheme for distributed TDMA system in wired world.

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