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家庭内センサーネットにおける信頼性無線フィードバック制御のための帯域効率化 MAC プロトコル

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ネットワークを用いたセンシングと制御を統合することで，家庭内エネルギーモニタリング・マネジメントを含む広い範囲のアプリケーションが可能となる．しかしながら，センシングと制御のためにネットワークメディアを共有することは，遅延やパケットロスの原因となる．本論文では，家庭内ネットワークにおけるセンシングと制御のため，メディアアクセス制御(MAC)層での信頼性無線フィードバックを扱う．ホームネットワークでのフィードバックは収集される多量のセンシングデータと関連することを前提に，信頼性フィードバック制御に必要とされる大容量の帯域要求と，共有ネットワークメディアでの限られた帯域の間で生じる矛盾によりもたらされる問題について議論する．そして，信頼性フィードバック制御要求に適した動的帯域割当方式を提案し，帯域利用効率を高めることで問題解決を行う．

Bandwidth-efficient MAC Protocol for Reliable Wireless Feedback Control in Home Sensing-Control Networks

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Integration of networked sensing and networked control leads to wide applications including home energy monitoring and management. Using shared network media for sensing and control introduces the delay and packet loss. This paper studies the Media Access Control (MAC) layer support of reliable wireless feedback for the sensing and control in home networks. Bearing in mind that the networked feedback in home network is associated with the collected large amount of sensing data, we discuss the problem caused by the contradiction between large bandwidth requirement of reliable feedback control and the limited bandwidth in the shared network media. We propose a dynamic bandwidth assignment approach that fits the reliability requirement of feedback control and enables a high bandwidth utilization to solve the problem.

1. Introduction

Networked sensing and control for smart home appliances are essential to the home energy management. By equipping each home appliance with sensors such as electric current sensors and communication interfaces, energy consumption of appliances can be monitored and controlled [1]. Home appliances periodically report the sensing data to the controller that is in charge of management and control of home appliances. Examples of control messages include changing power mode of appliances and adjustment of sensors' sampling rate, etc. The network communication media provides links between sensing and control of home appliances, and enlarges their operation scopes.

Feedback control is one of the important operations in smart home energy networks, since it performs as a response of controller to the sensing data of each home appliance. Successful feedback control enables the adaptive power adjustment of appliances, and copes with the unusual status at appliances, etc. The feedback control messages can be, for example, the average room temperature being sent to an air conditioner, the sampling rate to adopt at a home appliance, or a desired power mode of a home appliance [2].

Wireless feedback eases the connections between home appliances and a home controller. On the other hand, the wireless bandwidth constraint introduces the high possibility of packet loss and delays of packets in the sensing-control operations. The feedback control has a different requirement with regards to the packet delivery reliability and delays. Unlike sensing data, which are periodically sampled, delivered and are processed in a collective manner, a feedback control has a higher requirement on the reliability for successful packet delivery and confined delay. Loss or over-delay of feedback control message have an substantial impact on the successful home appliance operations such as power adjustment, and response to the unusual status etc.

Because Media Access Control (MAC) highly affects the success of packet delivery and delay in local home networks, this paper studies MAC mechanism for reliable wireless feedback. There has been much research effort directed toward efficient MAC for wireless networks and sensor networks [3]-[7]. However, few studies addressed the integration of networked sensing and feedback control operations in a shared communication channel, in which a control message generally requires a definitely reliable delivery within a certain delay, while sensing data ask for enough bandwidth for sending data packets.

Our target is to design a bandwidth-efficient MAC protocol for wireless networked sensing and reliable control. The desired MAC protocol should provide success packet delivery with delay guarantee for feedback control messages in home networks, while keeps the flexibility

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of sensing data collection. Due to the potential large amount of feedback packets corresponding to the sensing data of many appliances, we particular consider the bandwidth efficient issues to deal with the bandwidth constraints in wireless networks.

The contributions of this paper are as follows. First, we study the features of sensing and wireless feedback control, and introduce the design principles of MAC particular for networked sensing and feedback control. Second, we propose a reliable MAC protocol that formulates the collective use of bandwidth with time compartment of sensing and feedback control operations, providing both easy access for sensing data and reliable delivery of feedback control messages with delay guarantee. Third, to achieve the optimization of bandwidth usage, we propose a dynamic bandwidth assignment scheme based on a few control slots, which highly reduced the redundant pre-allocated bandwidth for reliable control. We highlight that the minimum frequency of control slot in the bandwidth optimization follows the Nyquist sampling theorem in that the minimum allocated control slots should have a 2-times frequency to the sensing-control frequency, in other words, 2 control slots in a sensing-control cycle.

The rest of this paper is organized as follows. Section 2 introduces related works. Section 3 describes the network model and design principles. Section 4 presents the proposed approach of MAC protocol and section 5 concludes.

2. Related Work

MAC protocols can be categorized as contention-based approaches (Aloha, CSMA, S-MAC [3], etc) and contention-less approaches (TDMA, CDMA, frequency hopping, etc). Contention-based approaches are widely utilized in the shared network media. For example, CSMA-based approaches are adopted in the Ethernet, WLAN, ZigBee. Those approaches have flexibility for easy media access, but also have the disadvantages of high probability of packet loss when there is large network traffic [4].

On the other hand, contention-less approaches have the advantage of the successful delivery of packets but with little flexibility. A typical contention-less MAC is TDMA, which divides time into time slots and allocates them to each node [5]. As for smart home appliances, the TDMA based MAC leads to the complexity of node configuration such as synchronization for the data transmission in each slot. The channel utilization is a problem in case there are a number of nodes in a network, since the slot is generally assigned for each node in the network even though it does not use the channel.

There are many studies focusing on the improvement of CSMA based MAC. IEEE 802.11 protocols include a reservation scheme that helps avoid collisions even in presence of hidden terminals. Collision avoidance uses the RTS-CTS frames. Although RTS/CTS exchange help avoid collision, it also introduces the delay and consumes bandwidth resources, especially in case of small data delivery in sensor networks.

IEEE 802.11e proposes a QoS supported MAC on the base of CSMA, with especially considering the multimedia data such as voice and video data. There are multiple levels of priority for data traffic to access channel. High priority traffic has a higher chance of being sent than low priority traffic. In other words, a station with high priority traffic waits a little less before it sends its packet, on average, than a station with low priority traffic. The time-constrained data such as voice and video data have higher priories than general data traffic. This enables the QoS improvement in the contention-based approaches but does not guarantee the successful delivery of packets.

Hybrid MACs attempt to combine contention-based and contention-less protocols, Such as ABROAD [6] and Z-MAC [7]. ABROAD integrates a CSMA based contention protocol within each slot of a TDMA allocation protocol. Each node has priority to access the channel in its assigned slot. Z-MAC has a similar idea but with a main target of improving channel utilization. In this study the time slot unit is supposed to be large enough for being used by various candidate nodes. Up to the present, most hybrid MAC approaches consider independent node operations in the network. Few studies consider delay guarantee for various types of messages, and correlations of nodes that operate for both sensing and control.

IEEE 802.15.4 and 802.11e also propose optional hybrid MAC mechanisms with contention-based access and contention-less access by utilizing a superframe. Time is divided into superframes. Each superframe consists of two period CFP(Contention Free Period) and CP(Contention Period). The superframe gives an option of adopting both contention-based and contention-less access control. But it is just a framework without specifying mechanisms for managing the network resource and providing delay guarantee.

We have proposed a QoS-MAC which considers the reliable networked control in home network [8]. Arbitrary networked control is the study object in the considered applications. The arbitrary control message in the paper consists of a few bits control message such as on/off control, and multiple control messages can be aggregated in a control packet. The feedback control is different with the arbitrary networked control in that the feedback may generate a potential large amount of control packets associated with sensing data. Furthermore, the size of a feedback control packet is generally similar to that of sensing data packets, and is generally larger than that of the small control messages such as on/off switch. Hence, the MAC layer in feedback control should particularly consider the features of feedback control and deal with the bandwidth constraint for the potential large feedback control messages.

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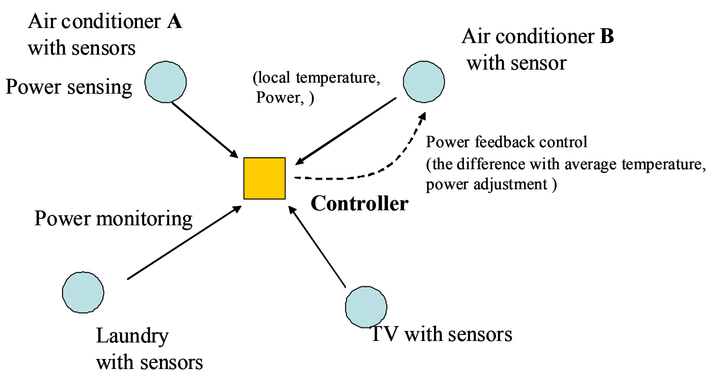


Figure1. An example of sensing-control model

3. System Model

3.1 Wireless Sensing-Control Model

As shown in Fig.1, a smart home network system consists of home appliances and a controller, which collects sensing data of home appliances and provides feedback control to the home appliances. Each home appliance is equipped with CPU, sensors and a communication interface, so as to have capability of computing, power sensing, and network communication. Each home appliance has a unique network ID to distinguish it from other appliances.

Sensors and the controller share the wireless communication media to delivery data to each other. The controller generates control packet according to the received sensing data. Each packet of sensing data might trigger a feedback control message as the response to the sensing data. An example of feedback control is illustrated in Fig.1. The controller sends the feedback, which includes the information of power adjustment and temperature, to an air conditioner B after comparing the received sensing data at the air conditioner with the average value of sensing data in the room.

Figure 2 illustrates the delivery of feedback control messages and collection of sensing data in the shared communication media. A feedback control message has a tolerant delay (TD), within which a control message is expected to be successfully delivered to the home appliance, as shown in Fig.2. The success of the feedback packet delivery requires the packet collision avoidance.

3.2 Design Principles

The design principles of QoS supported MAC are as follows:

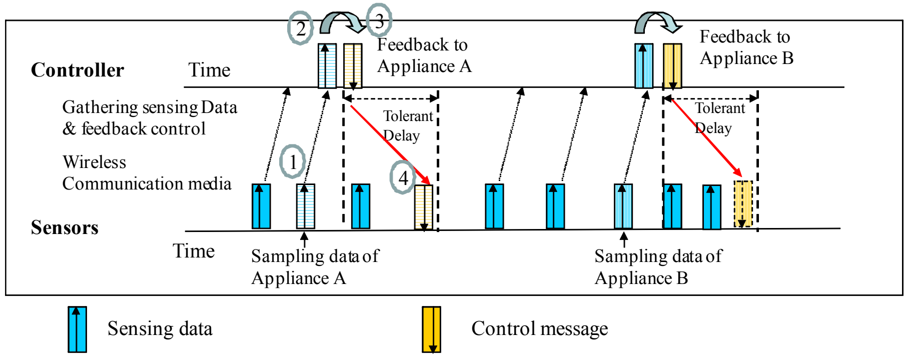


Figure2. Packet delivery in sensing and feedback control

(1. A sensor at appliance A reports a packet to the controller; 2. The controller receives the sensing packet; 3, the controller generates a feedback packet to appliance A according to the received packet; 4.the sensor at appliances A receives the feedback packet within the tolerant delay.)

(1) Successful delivery of feedback control messages - Each control message, when generated according to the received sensing data, should be delivered from a controller to appliances with a high successful delivery rate.

(2) Guaranteed delay - Each feedback control message should be received by appliances within the required tolerant delays.

(3) Bandwidth efficiency for potential large amount of feedback control messages- Under the principles of (1) and (2), utilization of communication channel and bandwidth should be efficient so that collection of sensing data has abundant available time of channel usage.

(4) Being simple for use and easy for configuration to home appliances.

4. Wireless Feedback MAC Protocol

We propose a wireless sensing-control MAC protocol of FCMA (Feedback Control Media Access) that aims to support reliable feedback control with bandwidth efficiency. According to the design principles described in section 3.2, we introduce the proposed protocol with two correlated parts- basic approach and advanced approach. The basic approach introduces how the FCMA supports successful delivery feedback control within the tolerant delay while keeping the easy access of communication media for networked sensing. The advanced part of FCMA introduces the bandwidth optimization for sensing and control on the basis of first part of the proposal.

4.1 Basic FCMA: Media Access Formation for Sensing and Feedback Control

Following the basic design principles, the desired MAC should let each successfully transmitted sensing packet be able to get a corresponding feedback within a confined delay in case the feedback is required. We can further observe that collective sensing data should be followed with collective feedbacks within the tolerant delay.

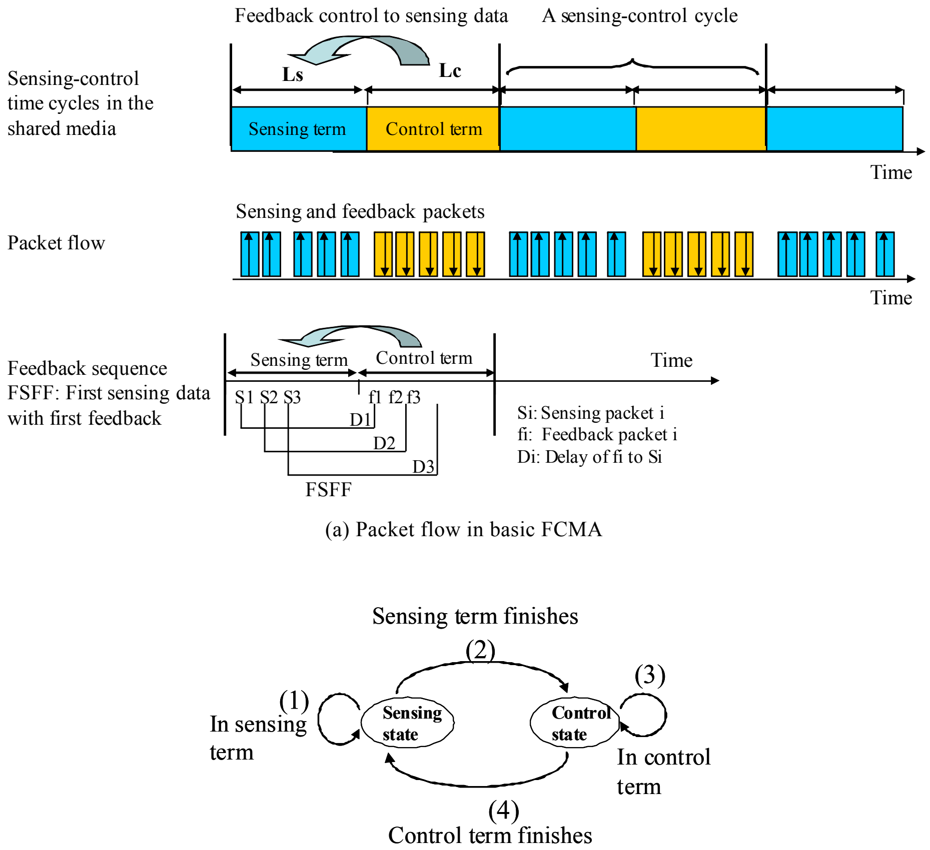
In basic FCMA, to enable success delivery of feedback control, the time is divided into continuous sensing-control cycles. As shown in the Fig.3(a), one sensing-control cycle consists of a sensing term and a control term. A control term follows a sensing term and is correlated with the sensing data transmitted in the sensing term. Each home appliance and controller formulates the time according to the sensing-control cycles so as to be in the same term simultaneously. Such formation of a sensing term and a control term enables each feedback successfully response sensing packets with a limited delay.

Figure.3 (b) illustrates the state transition diagram of home appliances and the controller in a sensing-control cycle. In a sensing term, both home appliances and the controller are in the sensing state. And home appliances access the communication media in an opportunistic manner, e.g. CSMA, to report sensing data, while the controller is in a receiving mode to collect sensing data from home appliances. In a control term, both home appliances and the controller are in the control state. And the controller transmits feedback control packets to home appliances, while each home appliance is in a receiving mode to get control packet from the controller.

Now the problem shifts to how to decide the term length of sensing and control. We define the length of sensing term and control term according to the principles with regard to control delay. Let Ls denotes the length of sensing term, and Lc denotes length of control term. Thus a period of sensing-control cycle is $Psc=Ls+Lc$, and the frequency Fsc of a sensing-control cycle is $Fsc=(1/Psc)=1/(Ls+Lc)$. Suppose a sensing packet that triggers for a feedback corresponding to only one control feedback packet that has same packet-size with sensing data packet. then $Ls=Lc$. Let Dm denotes the maximum delay of sensing data and suppose each control message has the same Tolerant Delay (TD). We can get the following proposition.

Proposition 1: The maximum length of a sensing term should be the tolerant delay of TD.

Proof: Note that the largest delay Dm of a feedback packet corresponding to a sensing packet should not be larger than TD. To minimize the largest delay of a feedback response to a sensing packet, the feedback should response the sensing packet in a "FSFF: First sensing data with first feedback" order, as shown in Fig.3(a). That is, the earlier received sensing packet should correspond to a faster feedback. Therefore, the largest delay of a feedback control packet is $Dm=Ls$. Consequently, the length of sensing term Ls should not be larger than TD to support that even the first packet in the sensing term can get a feedback within the tolerant delay TD.



(a) Packet flow in basic FCMA

(b) State transition diagram of home appliances and the controller

Figure3. Media access formation for Sensing and reliable feedback control

Furthermore we can know the bandwidth usage ratio of control term is

$$Rc=(Lc/(Ls+Lc)=50\%, \quad (1)$$

in case of a feedback packet that sensing data triggered has the same packet size of sensing data.

4.2 Advanced FCMA: Optimization of Bandwidth Allocation for Sensing with Relaible Feedback Control

The basic FCMA highlights the formation mechanism of time usage to support reliable feedback to each sensing data packet. The advanced FCMA aims to optimize the bandwidth efficiency on the basis of basic FCMA. The bandwidth efficiency is defined in the design principle 3. That is, under the support of reliable feedback control, the utilization of shared bandwidth should be efficient so that collection of sensing data has abundant available time for bandwidth usage.

Figure 4 illustrates the problem of bandwidth inefficiency in basic FCMA. The control term will include the redundant use of bandwidth in case there are sensing packets which do not ask for or trigger off the feedback control. As shown by the example in Fig.4, the first sensing term only requires the feedback to packets A and B. Therefore, only two feedback packets are generated in the control term, the left time for bandwidth usage in the control term is wasted. Such redundant use of control term is particular raised in case there are a large number of sensing data packets, which do not ask for the feedback control in response to the sensing data. The waste of bandwidth usage will potentially introduce many packet collisions in sensing data delivery.

To optimize the bandwidth efficiency, a straightforward approach is to fill in the redundant duration of control term with the sensing packets so as to increase the bandwidth utilization. However, there is a requirement of maintaining the reliable control to all sensing packets, including those being filled in the redundant control term.

According to the above discussion, we design a dynamic bandwidth usage mechanism that optimizes the bandwidth efficiency by minimizing the redundant duration of control term. The key idea is illustrated by Fig.5. Rather than proactive formation of the whole time of bandwidth usage into sensing and control term, the advanced FCMA adopts partial formation of bandwidth usage in its initial setup. That is, time is partially and proactively formulated by the periodic control slots that dynamically assign the length of each control term according to the requirement of sensing packets. Sensing packets are delivered in each interval from the time in a control term that the feedback is finished to the time that next control slot starts. We illustrate the sensing control procedure based on the example shown in Fig.5(a). At the beginning of sensing control procedure, the sensing-control cycle is divided with periodic control slots, at each control slot the controller gains the access to the communication media

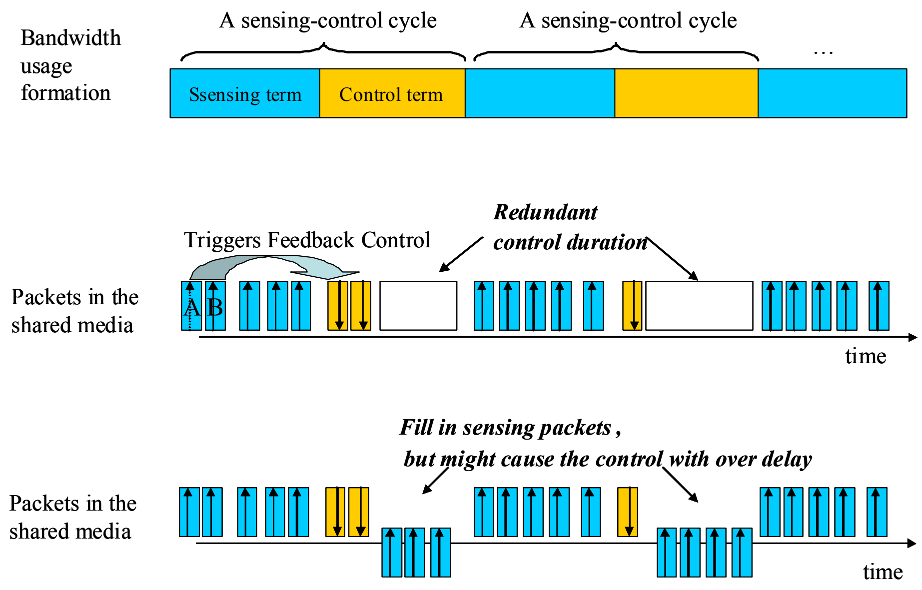
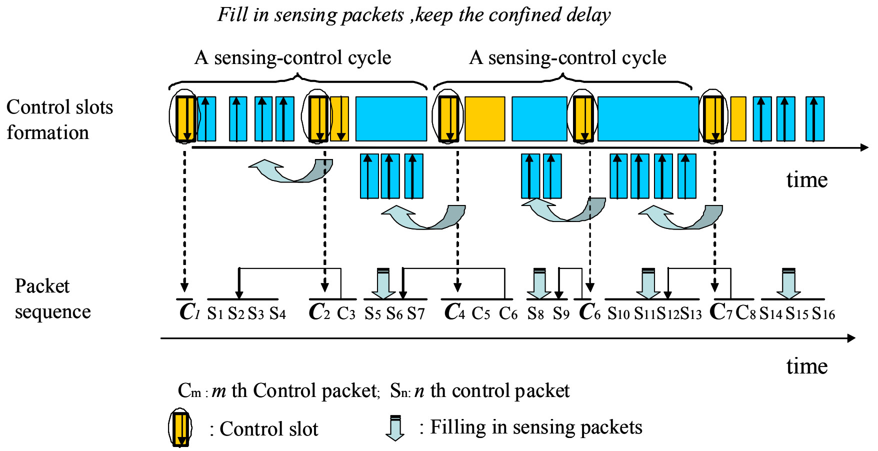


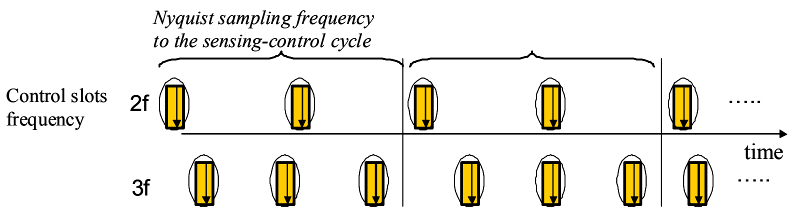
Figure4. Bandwidth efficiency problem in basic FCMA

and generates a control packet that includes feedback control information and also tells the appliances how many feedback control packets will follow. For example, control packets C1and C2 are initiated at the control slots in the first sensing-control cycle. Since C1 is the first packet in the sensing control procedure, it does not feedback to any sensing data, but sets the period of control slots to home appliances. Each control packet in a control slot can announce the number of feedback control packets in an on-demand manner. For example, packet C2 announces there are 2 control packets (C2 and C3) to home appliances. The number of feedback control packets announced in control slot is according to the sensing data received in the interval between the control slot and its previous control slot.

Proposition 2: Comparing with the period of the largest sensing-control cycle, the setup of control slot frequency follows a Nyquist sampling theorem. That is, the minimum frequency of control slots is 2 times of the largest sensing-control frequency. In other words, the minimum number of control slots in a largest sensing-control cycle is 2. This rule is applied to the cases that tolerant delay is larger than 1 packet slot time.



(a) Dynamic bandwidth usage in advanced FCMA



(b) Control slot frequency

(2f: 2 times frequency of sensing-control cycle, 3f: three times frequency of sensing-control)

Figure5. Advanced FCMA with formulation of control slots and dynamic bandwidth assignment

Proof. We use a proof by contrapostitive as follows. If the maximum interval between the two consecutive control slots is larger than *TD*, the feedback delay for the sensing data delivered in the interval between these two consecutive intervals might larger than *TD*. Thus in the periodic setup of control slots, the interval between two control slots should not be larger than *TD*. Note the largest sensing-control cycle denoted by *max_Psc* is two times of *TD*, therefore the *max_Psc* is 2 times of the largest interval of two consecutive control slots. In

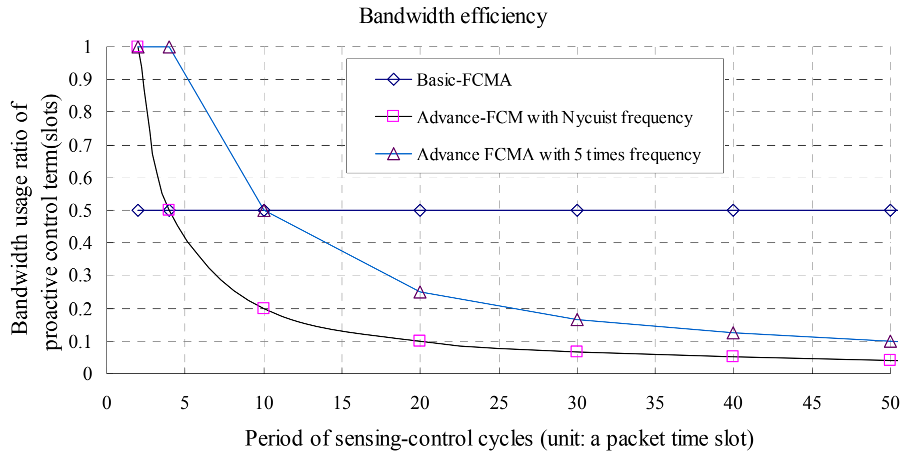


Figure6. Bandwidth efficiency performance

other words, the minimum frequency of control slots is 2 times of the largest sensing-control frequency.

With the minimum frequency of control slots, we can know the ratio bandwidth of control slots is:

$Rc\_A = 2/(Ls+Lc)$, (2)

in case of a feedback packet that sensing data triggered is with the same packet size of sensing data.

Figure 6 shows the band width efficiency of control terms (slots) with varying periods of sensing-control cycles. In fact, it reveals essential phenomena of designing FCMA. The bandwidth efficiency is highly impacted by the correlation of the control slot frequency and the largest sensing-control cycle, which is 2 times of *TD*. When the period of sensing control cycle is very small, and the frequency of control slot is large, the control slot will take all or most bandwidth usage and the basic FCMA performs better. In case the period of sensing control cycle is large and the frequency of control slot is small, the control slot will take relative small bandwidth usage, and the advanced FCMA has better performance. The control slot with the minimum frequency that is 2 times of sensing control cycle frequency, gains the smallest usage of bandwidth while keeps the success delivery of control packets within the tolerant delay. The larger the control slot frequency it is, the larger bandwidth is used by the control slots.

5. Conclusion

This paper introduced a bandwidth-efficient MAC approach- FCMA, for networked sensing and feedback control in home appliance networks. We describe the design principles especially for sensing and reliable feedback control. The proposed approach FCMA consists of two parts. Basic FCMA enables reliable delivery of control packets while keeps the flexibility of sensing data collection. On the other hand, the advanced FCMA optimizes the bandwidth usage by dynamic assignment of bandwidth usage. This paper also highlights that the highest bandwidth efficiency is achieved by adopting the minimum frequency of proactive control slots, such a frequency is two times of the sensing control cycle frequency.

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