Power Consumption Control Technology in WiMAX MAC Layer

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Reducing the power consumption of mobile stations (MSs) is one of the major issues for wireless broadband systems. The Mobile WiMAX standard defines Idle and Sleep modes to reduce MS power consumption by suspending the operation of the MS. In addition, this standard defines a protocol that enables the MS's transmitting power to be controlled from the base station. However, manufacturers should consider how to implement these modes and a protocol for using them. In this paper, we describe mechanisms for implementing the Idle and Sleep modes in an MS using the functionality of the media access control (MAC) layer. We also describe a novel transmission power control algorithm that can reduce power consumption.

1. Introduction

Wireless systems have recently been becoming faster and more intelligent. Many people now use wireless systems not only for voice communication but also for data communication such as e-mail, web-browsing, music downloading, and payments. In the upcoming decade, communication by wireless access will become much more convenient than that by wired access. However, the high-speed access and intelligence make the power consumption of wireless systems high. This means that a large-capacity battery is required in a mobile station (MS), or the battery will not last long. To avoid such degradation, reducing MS power consumption is one of the main issues for wireless broadband systems. Advances in semiconductor processing enable reductions in power consumption, but it is also possible to utilize the functionality of the media access control (MAC) layer to a great extent to reduce power consumption.

In this paper, we present mechanisms that will be installed in the MS or base station (BS) to reduce MS power consumption. In section 2, we describe two types of power saving mechanisms that are installed in the MS to implement the Idle and Sleep modes defined by IEEE 802.16e-2005.[1] These modes suspend the operation of an MS. IEEE 802.16e-2005 also defines a protocol that enables an MS's transmission power to be controlled from the BS to achieve a stable wireless connection. In section 3, we describe a novel transmission power control algorithm installed in the BS. It can reduce the power consumption of an MS without degrading the stability or throughput of the wireless connection.

2. Power reduction mechanisms in MAC layer of MS

2.1 Overview of MAC architecture in MS

As the WiMAX protocol is a new standard, it is necessary to support future enhancements of the protocol in a flexible manner. The MAC hardware diagram for the MS is shown in **Figure 1** and the MAC software structure for the MS is shown in **Figure 2**. We chose to use an architecture in which the lower MAC (LMAC) is

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implemented in hardware while the upper MAC (UMAC) is implemented in software. LMAC assembles protocol data units (PDUs) from bursts and constructs sending bursts. Data encryption and decryption are also implemented in LMAC. The remaining processing is done in UMAC on two processor cores: an FR-80 core executes the "FR-L" portion and an ARM™946[note] core executes the "ARM" portion. FR-L mainly performs disassembly/reassembly of MAC service data units and traffic management. ARM mainly performs control protocol processing and MS state management. As data should be received and transmitted according to WiMAX frame timing, highly real-time processing is required. On the other hand, procedures for control processing are suitable for being executed concurrently. As those characteristics are different, we chose to execute them on separate processor cores. Moreover, we assumed that the processor core that executes the control processing will also execute the application layer software in future, so we chose to use an ARM core for the control processing.

2.2 Power management mechanisms in MAC layer

For MS power consumption reduction, the following two power saving controls are implemented in UMAC software that we developed:

1) Processor local power management using a power saving operation implemented in each processor core
2) Power saving operation that suspends the entire interface block

The former is achieved when there is no instruction to be executed by the processor. The latter is achieved when the MS enters a state in which it does not transmit or receive any data. The two controls operate independently and complementarily. Power consumption control in the physical layer (PHY) of LMAC in an

note)   ARM is the trademark of ARM Limited.
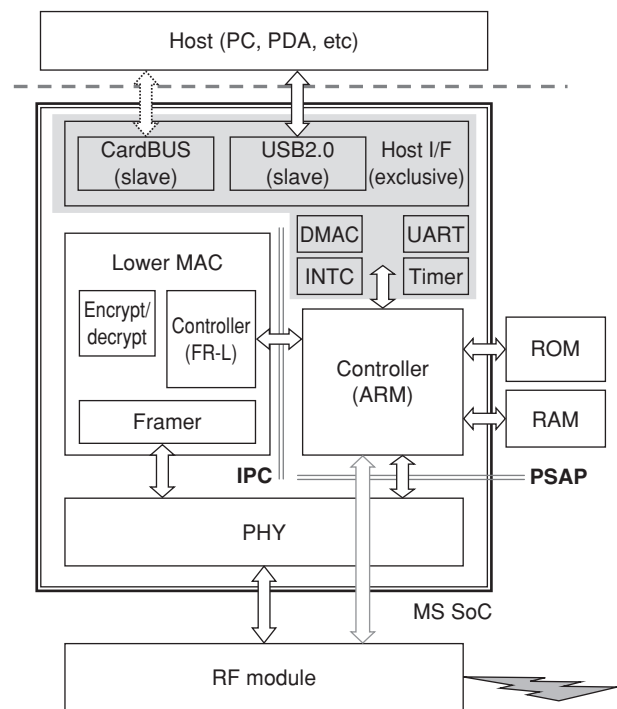
DMAC: Direct memory access controller
INTC: Interrupt controller
IPC: Inter processor communication
PSAP: PHY service application programming interface
UART: Universal asynchronous receiver transmitter

Figure 1
MAC hardware diagram for MS.

intra-frame cycle is also achieved by hardware autonomously.

2.2.1 Processor local power management

The power saving control by the processor local power management is achieved when the operating system enters the idle state (i.e., when there are no tasks to be executed). With this control, each processor enters the power down state, which is implemented in processor core logic. When asynchronous events (i.e., hardware interrupts) occur in a processor, it exits the power down state and enters the normal execution state.

2.2.2 Control suspending interface block
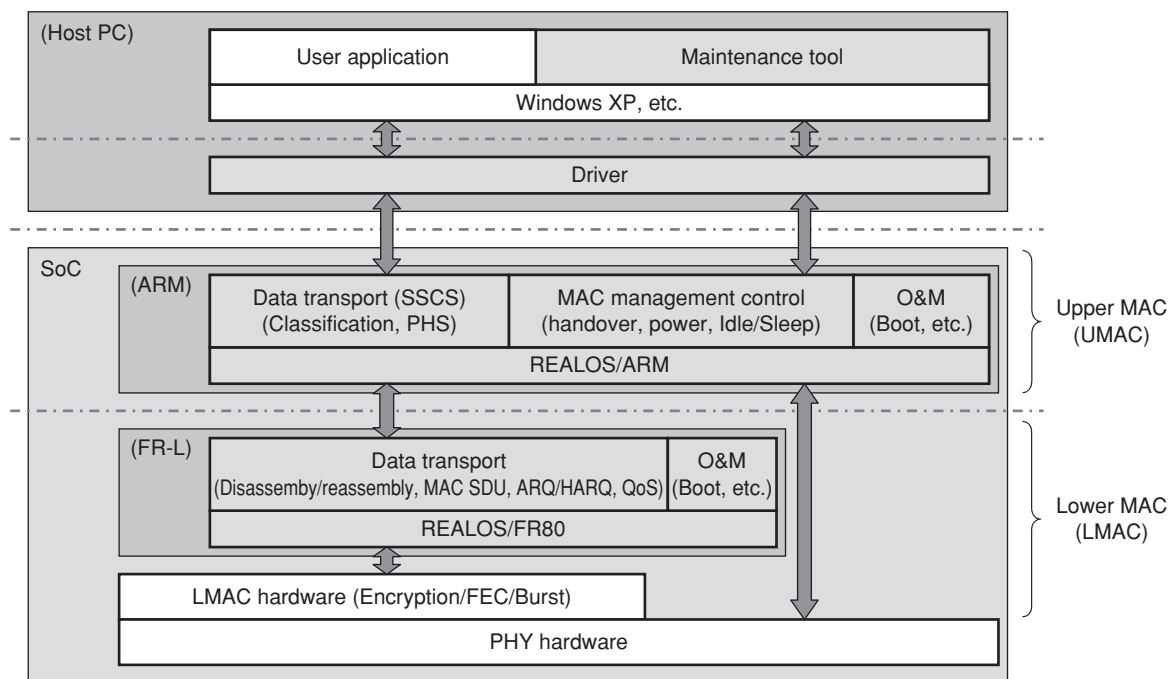
In normal operation, as each block of the

Figure 2
MAC software structure for MS.

interface acts in a pipelined manner, there is no chance to stop all of the blocks at the same time. For this reason, power consumption control in an intra-frame cycle is achieved separately in each hardware part. On the other hand, power consumption control that suspends the entire interface block is performed when the firmware detects a period in which the MS is neither receiving nor transmitting. The MS must be "out of service" and "in Idle or Sleep mode" in order for the software to detect this period.

1) Idle and Sleep modes

The WiMAX protocol defines an Idle mode and a Sleep mode, in which transmitting and receiving operations are suspended. The Idle mode is a mode in which the MS does not communicate with a serving BS (SBS), but maintains communication with a BS that has a paging controller function (i.e., a Paging BS [PBS]). Here, the SBS and PBS can be the same physical equipment. In this mode, the BS maintains the context of the MS so that the communication

with the BS can be restarted immediately. The MS periodically observes the broadcast message from the Preferred BS (which is also the Paging Controller) in order to learn whether there are any new messages for it at the BS. Therefore, the Idle mode can be used as a state for standing by for the arrival of new messages.

The Sleep mode is a mode in which the MS intermittently transmits and receives data over connections between the BS and MS. The periods of no transmission and reception (stop periods) of each connection are not necessarily synchronized. The period when all connections are in the stop period is called "unavailable" and the MS can stop the operation of the wireless interface. In the unavailable period, the BS can decrease its processing load related to the MS, and the MS can reduce its power consumption by suspending the wireless interface block. The Sleep mode is suitable for low-bit-rate and continuous-data communication, which can tolerate latency, such as video streaming of quarter video
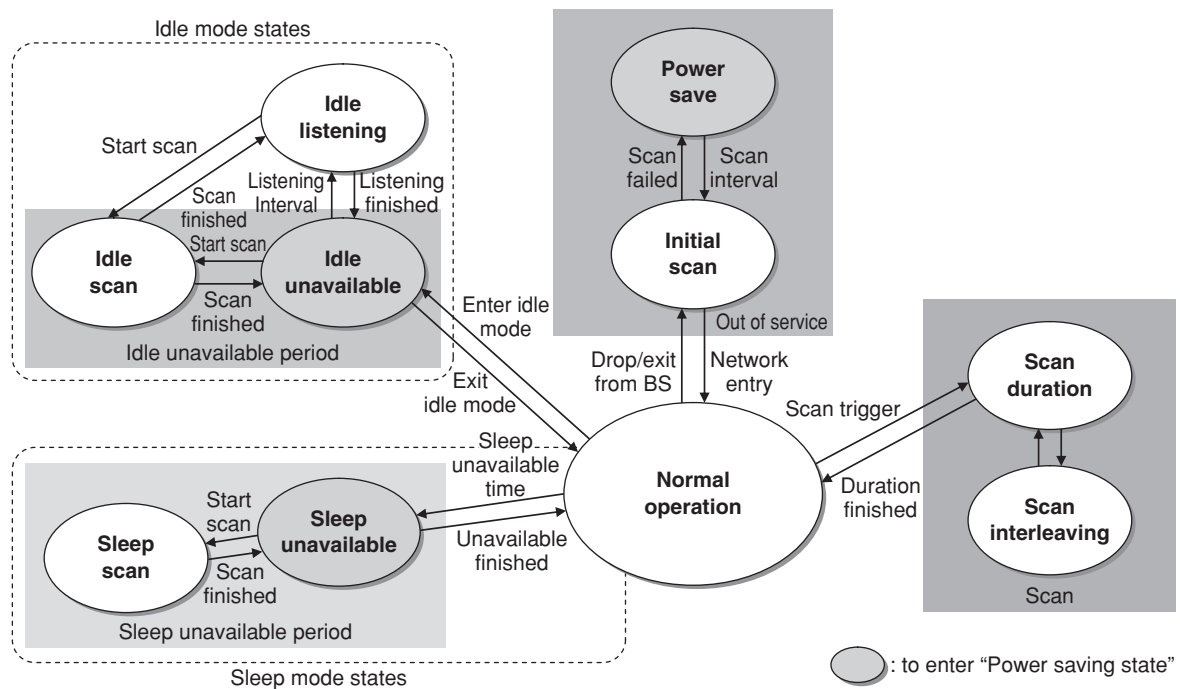
Figure 3
MS MAC state.

graphics array (QVGA)- or common intermediate format (CIF)-sized images.

2) MS MAC state

An MS MAC state transition diagram is shown in **Figure 3**. An MS in the out-of-service state regularly scans for BSs. As the MS does not communicate between the scanning operations, the wireless interface can be deactivated in this interval. If the MS detects a BS during the scanning and succeeds in entering a network, the MS enters a state in which it is connected with a BS. If the MS is in Idle mode after negotiating with a BS, it repeats a listening period for receiving broadcast messages and an Idle mode unavailable period in turn. If the MS is in Sleep mode after negotiating with a BS, it goes into a Sleep unavailable period if all the connections are in the stop period; otherwise, it stays in the normal operation state. There is a case where the MS runs the wireless interface in the Sleep unavailable period or in the Idle unavailable period. When the receiving signal level

from a BS is low, the MS performs BS scanning to search for candidate BSs for handover during those unavailable periods. Therefore, the periods when the interface can be completely stopped are the periods when the MS is not scanning during the unavailable periods. These states are labeled "Power save", "Idle unavailable", and "Sleep unavailable" in Figure 3. The MS enters a low power consumption state in these states by suspending the entire interface block.

3) Low power mode procedure

The blocks of the MS hardware for transmitting and receiving work in a pipelined manner. Therefore, an operation suspending the entire interface block will be executed in a phased procedure, as shown below:

• ARM sends FR-L an instruction to stop the transmitting procedure to avoid operations using unavailable resources during the suspension period.

• When the frame sequence number reaches a target time, ARM suspends the PHY and

LMAC parts by stopping the clock supply.

- ARM sends FR-L an instruction to stop the processor core, sets the external memory to standby mode, and sets a wake-up timer; it then stops its core itself by stopping the clock supply.

Possible triggers for wakeup are expiry of the wakeup timer and a wakeup request from a host PC. When the wakeup logic detects a wakeup trigger event, it restarts supplying the clock to the processor core. Then, the ARM sets up a clock generator to restart each block, sets up external memory for normal operation, and sends FR-L the instruction to restart.

As the time required to receive a restart depends on the frame synchronous status of PHY, if the period in which the entire interface block is suspended is shorter than a threshold, the MS keeps active the circuit necessary to maintain the frame timing during the suspension period in order to shorten the time taken to resume.

With the first-generation system-on-a-chip (SoC), the power consumption of the module is expected to be decreased to about 30% by entering the Idle mode. If the power consumption is reduced by suspending the entire interface block and the transition time required for suspending or resuming is reduced in a next-generation device, the operating time of a portable device should increase greatly.

3. MS transmission power control

In the WiMAX system, the BS controls the transmission power of the MS in the same way as in the code division multiple access (CDMA) system. In the CDMA system, the BS strictly adjusts the transmission power of MSs to equalize the powers received at the BS. This transmission power control (TPC) is necessary to separate the signals of multiple MSs by CDMA decoding.[2] In the WiMAX system, on the other hand, the MS transmission power is controlled in order to avoid exceeding the BS's total receiv-ing power from an antenna. In the WiMAX standard,[2] other uses of it are not defined (i.e., the uplink TPC algorithm is vendor specific).

The WiMAX system supports adaptive modulation and coding (AMC), which varies the modulation, such as quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM), or the error correction coding rate according to the wireless channel quality. For the MS to transmit a signal, the BS determines the modulation and coding scheme (MCS) by observing the signal-to-interference-and-noise ratio (SINR) of the received signal. MCS information is transmitted for each MS. If the SINR is good, the MS can use high-speed modulation and a small amount of error correction code, so a high transmission rate can be achieved. One way to improve the SINR is for the MS to transmit at high power (i.e., by increasing the signal strength). However, increasing the transmission power increases the battery power consumption, so the battery lifetime becomes shorter. In the WiMAX system, the BS assigns sub-channels for each subordinate MS to avoid interference, but if the MS transmission power is increased, it might interfere with MSs under other BSs. An MS that experiences interference with its signal increases the transmission power to maintain the transmission rate. This shortens the battery lifetime even more. As the battery lifetime is critical for an MS, it is very important to control the MS transmission power, taking into consideration the transmission rate and battery lifetime.

3.1 MS TPC algorithm

We developed an MS TPC algorithm that is implemented in the BS to prolong battery lifetime. The behavior of our algorithm is shown in **Figure 4**. The concept is that the lowest-rate (most-robust) MCS is used as much as possible because the required transmission power is the lowest. Specifically, the BS designates the lowest-rate (most-robust) MCS such as QPSK 1/2 for each MS when all the data requested to be
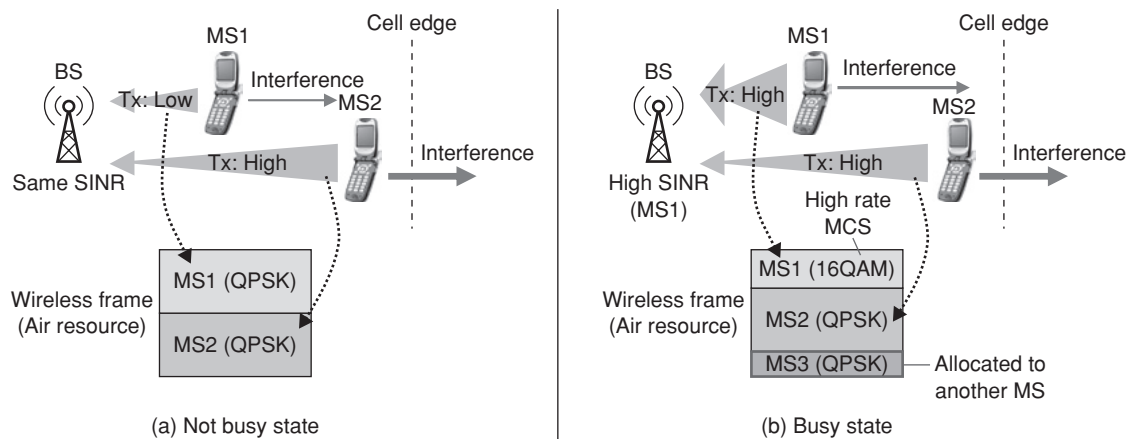
Figure 4
TPC algorithm overview.

transmitted from MSs can be transmitted using that MCS. A transmission power for each MS is also designated as the minimum level that guarantees transmission in that scheme. If the total data requested to be transmitted exceeds the transmission capacity for that MCS, the BS selects an MS that does not interfere with most of the MSs under other BSs and designates a higher-rate MCS for that MS by boosting (i.e., increasing SINR) the MS transmission power to a level that guarantees transmission using the new MCS. Using the higher-rate MCS reduces the air resources required for the MS. Consequently, the BS can allocate the released resources to other MSs. To select the MS that interferes the least with MSs under other BSs, the transmission power of the MS is used as a measure. If the MCS of each MS is the same, the transmission power of the MS suffering the least interference from MSs under other BSs is the lowest because the required SINR is the same. This is because the effect of interference is symmetrical; in other words, the MS receiving the least interference causes the least interference. The MS that transmits at the lowest power is selected as the MS to send at the higher-rate MCS at the higher transmission power.

3.2 Simulation

To evaluate our algorithm, we developed a system-level simulator that calculates the SINR of a BS receiving signal for a specific MS uplink. Based on the SINR, the simulator also calculates the maximum transmission rate using the required SINR for each MCS. The method is shown in **Figure 5**. The signal that BS1 receives from MS1 is treated as a signal and its power at BS1 is calculated. Signals received from other MSs (MS2-0 to MS2-5) under other BSs are treated as interference and their powers at BS1 are calculated and summed. With the addition of a certain amount of random noise power to the interference, MS1 SINR is calculated. In a simulation, MSs in the neighboring six cells were treated as sources of interference. The simulation conditions are given in **Table 1**.

The average transmission power for various numbers of connections is shown in **Figure 6**. The lower line is our algorithm and the upper line is for a legacy algorithm that selects the highest rate MCS at a given SINR. As the number of MSs (connections) changes as they move, in many cases our algorithm reduces the power consumption of the MS by reducing the transmission power while also reducing interference.
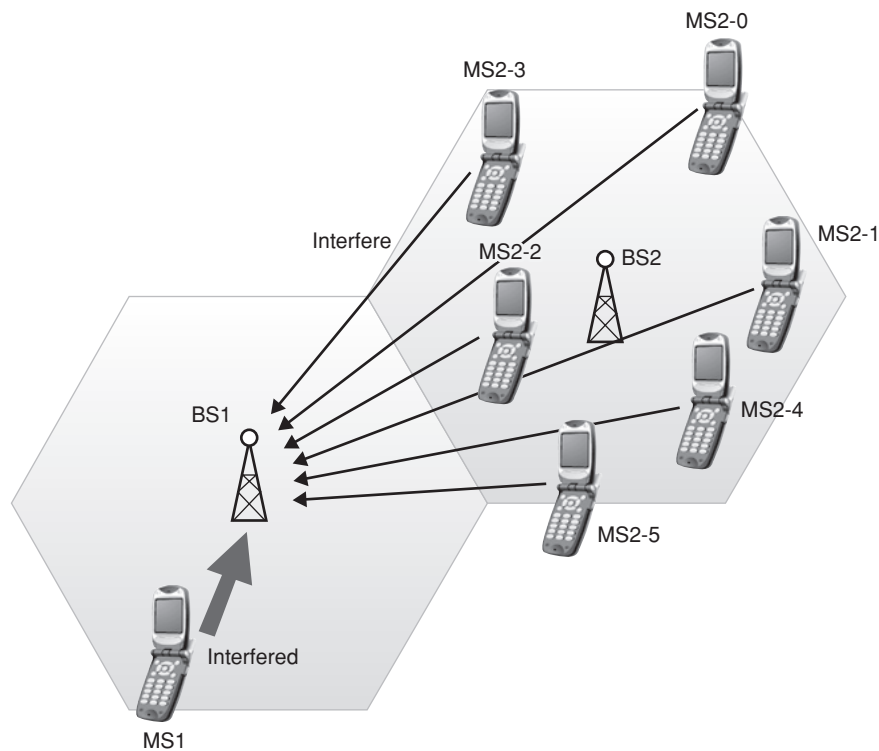
Figure 5
Simulation method.

Table 1
Simulation conditions.

	Item	Value
Network structure	Cell structure	Omni
	Number of cells	7 cells
	Radius of cell	1 km
	Number of MSs (connection)	28, 32, 36, 40, 44
Scheduler	Algorithm	Round robin
	Modulation and coding	QPSK (1/2), QPSK (2/3), QPSK (3/4)
		16QAM (1/2), 16QAM (2/3), 16QAM (3/4)
Transmission power control	Required SINR for QPSK	3 dB (1/2), 6 dB (2/3), 9 dB (3/4)
	Required SINR for 16QAM	11 dB (1/2), 14 dB (2/3), 17 dB (3/4)
	MS max Tx	23 dBm
Channel model	Path loss	ITU-R vehicular

4. Conclusion

In the WiMAX system, Idle and Sleep modes and a protocol for TPC are defined to reduce the power consumption of the MS as a standard. To achieve low-power systems using these modes, mechanisms to reduce the power consumption in each mode are necessary. In this paper, we described mechanisms installed in the MAC layer functionality of the MS. We also described a novel TPC algorithm installed in the MAC layer of the BS that utilizes the protocol. The algorithm reduces the MS transmission power
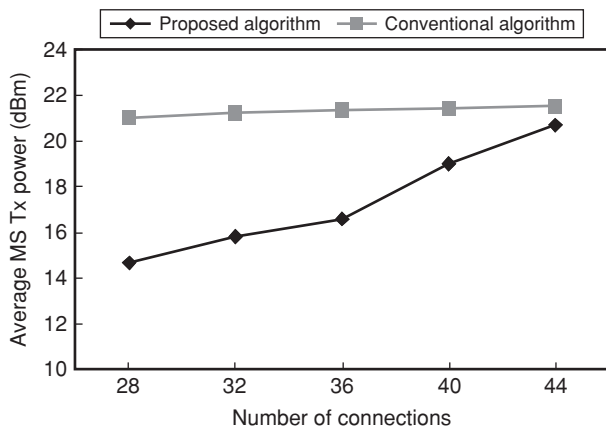
Figure 6
Simulation results.

in normal conditions while maintaining the connection quality. As a result, the MS power

consumption is also reduced.

Power consumption reduction will become more and more important. We will continue to evaluate the efficiency of these mechanisms and study more efficient methods for the future.

References
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2) R. Kohno, R. Meidan, and L. B. Milstein: Spread Spectrum Access Methods for Wireless Communications. *IEEE Communications Magazine*, **33**, 1, p.58-67 (1995).

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