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Proposal for IEEE 802.16m Sleep Mode Operation

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1. Introduction and Background

Sleep mode is proposed in IEEE 802.16e-2005 STD [1] standard as a power saving mechanism. Sleep mode is intended to minimize subscriber station (SS) power consumption and decrease the usage of air interface resources. While in sleep mode the SS alternates between intervals of availability and unavailability. During an unavailability interval an SS may power down its radio interface(s). On the other hand, during availability interval the sleep SS listens for a traffic indication message sent by the BS to indicate the presence of traffic. The SS in sleep mode may also send and/or receive traffic during the availability interval. The operation of sleep mode is illustrated in Figure 1 that shows the availability intervals (AI) and unavailability intervals (UAI) of a sleep mode SS.

In this contribution an attempt has been made to enhance the following aspects of sleep mode operation in IEEE 802.16m.

1. Minimize the air-link resource usage associated with sleep mode operation
2. Maximize terminal power saving during sleep mode operation

This contribution proposes the following methods to address these aspects:

[1] Mechanisms to enable an MS in sleep mode to send and/or receive traffic without terminating its sleep mode operation, thereby eliminating the need for sleep mode termination and re-activation during bursty traffic sessions such as web browsing. The elimination of sleep mode termination and re-activation has the following advantages: (1) it eliminates the repeated slow start behavior of the sleep mode in the reference system, thereby achieving better power saving; (2) it eliminates the air-link resources used during sleep termination and re-activation as well.

[2] Mechanisms to change the sleep pattern of an MS in sleep mode to better adapt to traffic pattern.

It is imperative to identify the issues with the design and performance of sleep mode operation of the reference system [2] before providing any new solution. Therefore, in the following section the performance of sleep mode operation in mobile WiMAX reference system are critically reviewed.

1.1 **Sleep mode operation in IEEE 802.16e-2005 STD**

In IEEE 802.16e-2005 STD the duration of AI remains fixed whereas the duration of UAI may double up to a maximum value or remain constant. The duration of the first UAI is denoted as *Initial UAI* and the duration of the unavailability interval at a particular time is given by

UAI = min (2(Previous UAI), Final UAI base*2^(Final UAI exponent) ------------------------ (1)*

Where *Final UAI base* is the final UAI base and *Final UAI exponent* is the final UAI exponent. It may be noted that when *Final UAI base* = *Initial UAI* and *Final UAI exponent* = 0, the duration of UAI is constant.

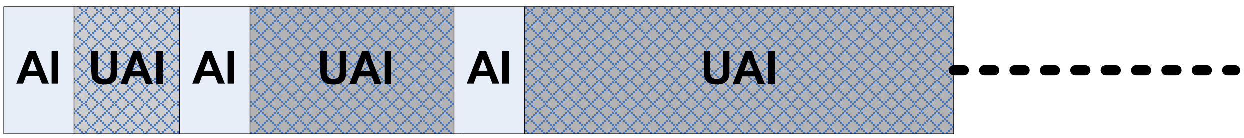

Figure 1: Illustration of sleep mode operation.

An SS in sleep mode may power down during the UAI, where as the SS wakes up during AI and listens for any MOB_TRF-IND message. SS's behavior upon receiving MOB_TRF-IND message is as follows.

1. If the MOB_TRF-IND message indicates that there is no traffic for the sleep mode SS, then the SS may choose to go back to sleep after receiving the message.

2. If the MOB_TRF-IND message indicates that there is traffic for the sleep mode SS, then the behavior of SS after the unavailability interval depends on the Traffic_Triggered_Wakening_Flag (TTWF) [1] (it may be noted that TTWF is negotiated between the BS and SS prior to SS enters the sleep mode).

   a. If TTWF = 0, the SS does not deactivate its sleep mode after the unavailability interval. Therefore, the SS continues its sleep mode as usual. This option allows a sleep mode SS to receive traffic during its availability interval without disrupting SS's sleep mode operation. Thus when TTWF=0, the SS exchanges DL/UL traffic during the remaining part of availability interval same way as in the state of normal operation (by normal operation, we mean the state when an SS is not the sleep mode).

   b. If TTWF = 1, the SS deactivates its sleep mode. Therefore, SS's sleep mode is terminated and it comes back to normal mode of operation after the unavailability interval.

Analysis of the sleep mode operation in IEEE 802.16e-2005 STD based systems:

Next, we present the advantages and disadvantages of the sleep operation procedures used in the reference system.

Disadvantages

1. Frequent termination and re-activation of sleep mode operation for bursty traffic: Although the sleep operation in the reference IEEE 802.16e-2005 STD allows an MS in sleep mode to send and/or receive traffic during the AI intervals using TTWF=0, the amount of traffic that can be exchanged is small because the length of AI interval is typically small. Therefore, in most of the cases, sleep mode is terminated when an MS in sleep mode has to send and/or receive traffic. This results in frequent termination and re-activation of sleep mode operation especially for sessions with bursty traffic pattern. Figure 2 illustrates the sleep operation in reference system for DL bursty traffic. As shown in Figure 2 sleep mode is initiated/re-activated in the absence of the DL traffic for an SS. While in sleep mode the SS alternates between AI and UAI. During sleep mode UAI can be modified using Eq. (1). Upon receiving positive MOB-TRF-IND message the SS terminates its sleep mode and transition to normal mode. After the completion of the burst of traffic the SS again goes back to sleep mode. It may be noted that in this illustration TTWF=1. Frequent initiation and termination of sleep mode operation results in the following disadvantages.

1. As air-link resources are used to carry signaling messages related to sleep mode termination and re-activation, frequent sleep initiation and termination results in higher air-link signaling overhead.
2. The UAI interval starts from the minimum value after each sleep initiation. Thus, frequent termination and initiation of sleep mode results in lower power saving as every time the sleep operation is terminated and re-activated, the UAI starts from its initial value leading to slow start phenomenon. This results in smaller duty cycle during the sleep mode operation resulting in lower power saving.

As an example, a simulation was run using Sleep mode with HTTP traffic with TTWF = 1, and TIR = 1 simulating a 1 hour long user web session in OPNET. The results are as follows:

Table 2: Simulation results for 802.16e mode for HTTP traffic

Total simulation time	60 minutes
% of Total simulation time data traffic exchanged[1]	0.6%
Total Time spent in Sleep mode[2]	94%
Total Time spent in Unavailability Interval[3]	95.5 %
Total Time spent in Availability interval	4.58%
Total # of Re-activation events	872
Average duration in Sleep mode	12 seconds

Notes:

1. The sleep trigger algorithm used a simple scheme of re-activating sleep after period of inactivity (no UL/DL data packets) lasting 4 frames.
2. The simulation did not take into account loss of control messages or the latency involved in sending and receiving confirmations to re-activate Sleep mode and thus, this number is probably going to be much less.
3. The simulation used a very ideal Listen interval of 2 frames, which in practice is not adequate for the MS to obtain a UL bandwidth allocation using the contention-based CDMA BW-Req allocation mechanism [1].

These figures are for only a single web session. In a network with tens or hundreds of users, the messaging overhead could potentially be very high. Thus 16e sleep mode is very expensive in terms of signaling overhead.

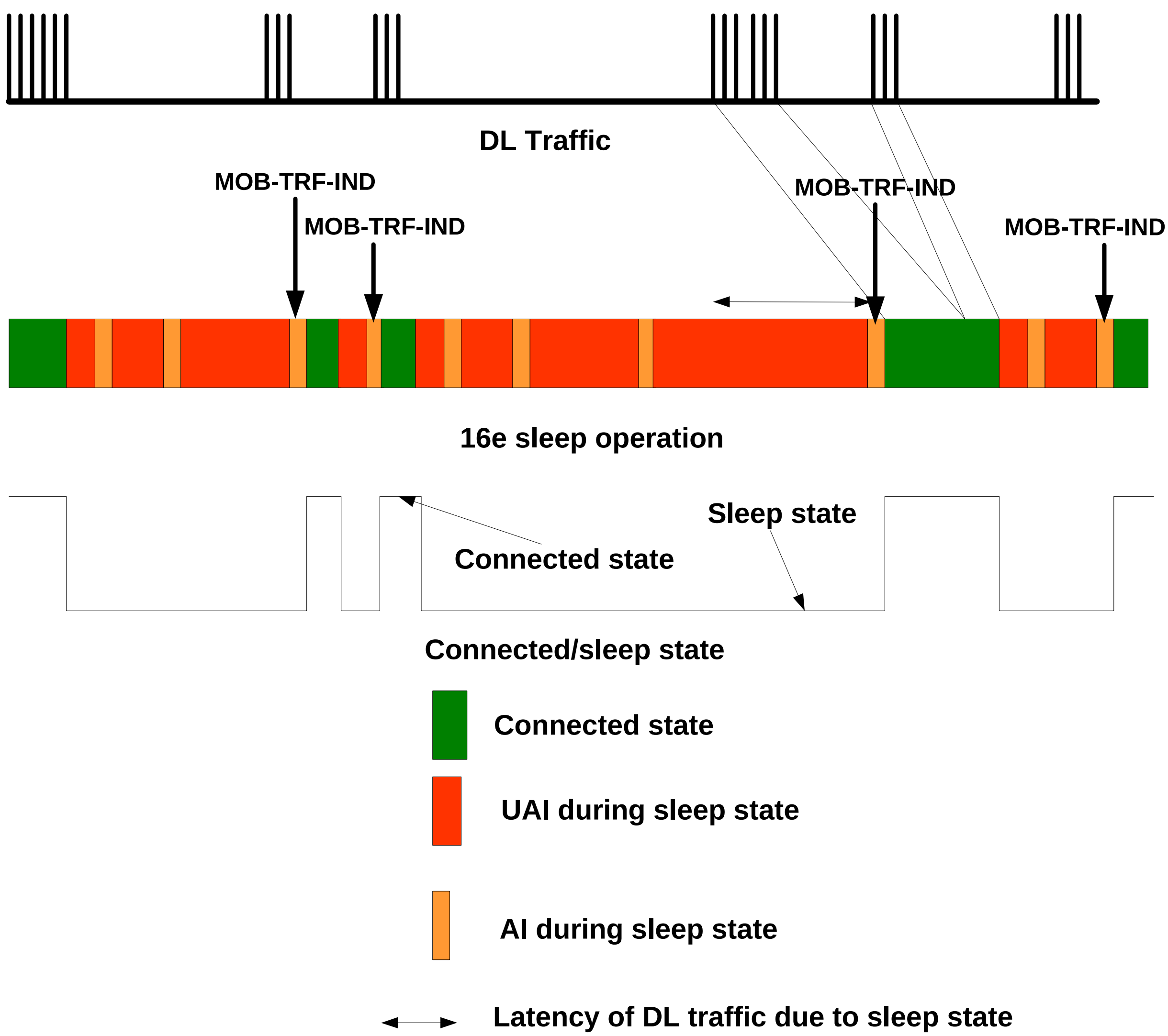

Figure 2: Illustration of sleep operation in 16e for bursty DL traffic.

Advantages

Although the sleep operation in the reference system has the above disadvantages, because of its simple operation it is easy to implement.

1.2 Summary of Issues with the Reference System Sleep Mode Operation

The above described short comings of reference system sleep mode operation motivate design to enhance the sleep mode operation in the IEEE 802.16m system to address the following issues.

1. Minimum signaling overhead associated with sleep mode operation.
2. Maximize power saving during sleep mode operation.
3. Sleep mode operation should track the dynamic traffic pattern as closely as possible.

Also, there are a few desirable characteristics of sleep mode operation as follows:

1. The sleep mode operation in 16m should be close to the ideal sleep operation desired as described below.

2. Sleep Mode Operation Design Considerations

Ideally the sleep mode operation in IEEE 16m should be designed in such a way that an SS is in connected mode during the presence of DL and/or UL traffic and it is in sleep mode otherwise. This desired sleep mode is shown as ideal sleep mode in Figure 3 where the connected mode and sleep mode closely follow the traffic pattern of the SS. This ideal sleep mode minimizes the latency introduced into DL traffic because of sleep operation and maximizes the duty cycle of the SS, i.e., maximizes the amount of time that the SS spends in sleep mode.

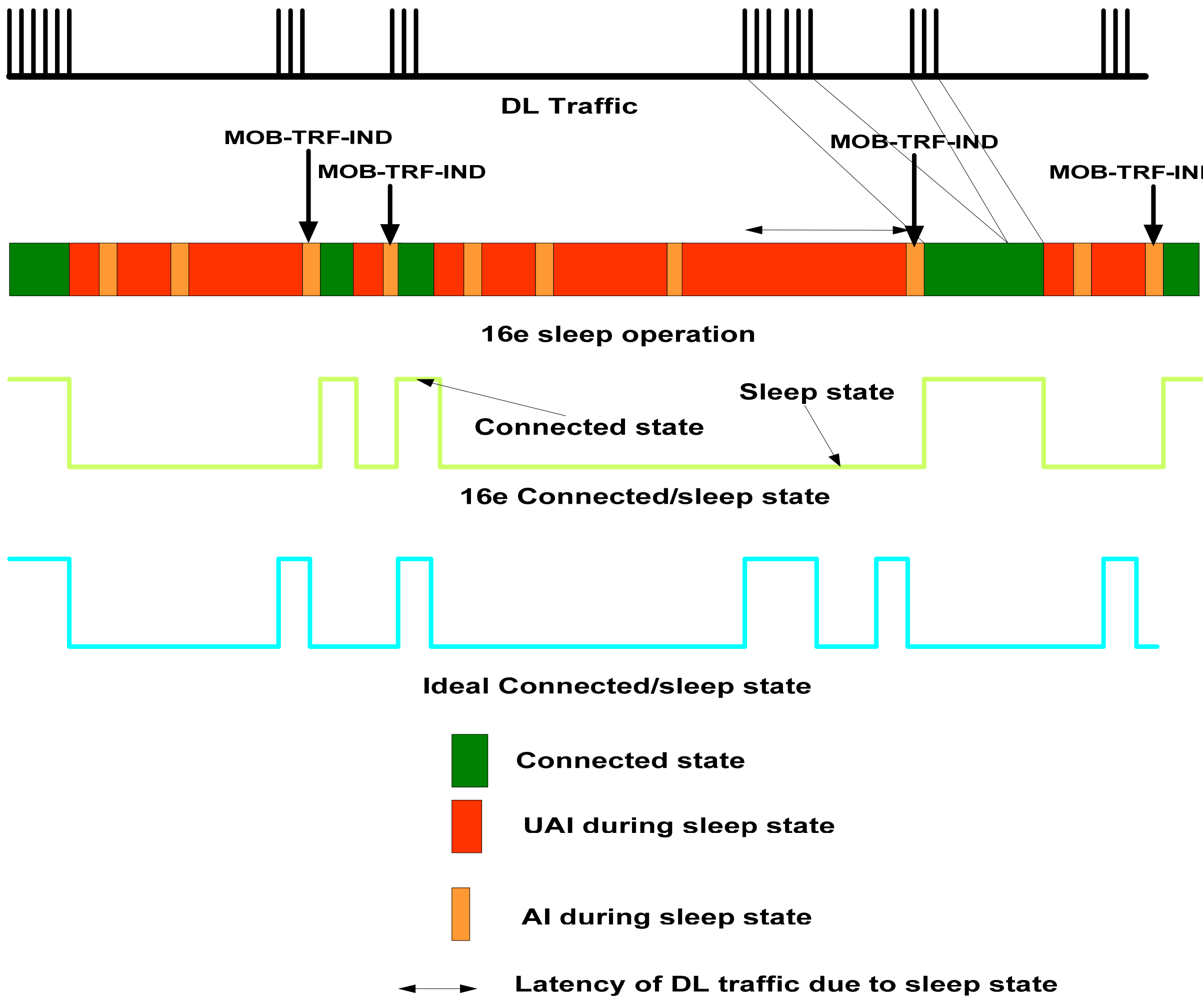

Figure 3: Illustration of ideal sleep operation and 16e sleep operation.

Improved sleep operation in the IEEE 802.16m system requires a careful consideration of the desired features listed in Section 1.2. The following sub-section proposes methods to achieve each one of these features.

2.1 Minimize signaling overhead associated with sleep mode operation

Reduction of signaling overhead associated with sleep mode operation is achieved by using the concept of pseudo unavailable interval (PUAI). The concept of pseudo unavailability interval (PUAI) enables the sleep mode SSs to send/receive bursty traffic in an efficient way without terminating their sleep mode. The PUAI is a part of the one or more unavailable intervals that is used, whenever necessary, by a sleep mode SS to send/receive traffic. In this case, the sleep mode operation, referred to as background sleep mode in the remaining part of this document, is not terminated. The PUAI interval can be understood as overlaying the additional available interval on top of this background sleep operation. The proposed PUAI concept is illustrated in the figure 4.

In this case, the background sleep operation is always active and alternates between AI and PUAI. Similar to the reference system the AI interval is small and fixed; UAI starts from a small value and incremented using Eq. (1).

When there is DL data waiting for a sleep mode SS, the BS sends positive traffic indicator in the MOB-TRF-IND during said SS's next AI. Along with MOB-TRF-IND the BS also conveys the PUAI duration for which the SS needs to remain in normal mode of operation, i.e., in a state where the SS can exchange traffic with the BS. It may be noted that in this case, the background state machine is not affected by the PUAI message. Thus, the overall state of the SS is determined as follows.

```
If (PUAI in ON) {
        SS is in normal operation mode
        }
If (PUAI is OFF) {
        If (AI is ON) {
                SS is in listening mode
                }
        Else {
                SS is in unavailable mode
                }
        }
```

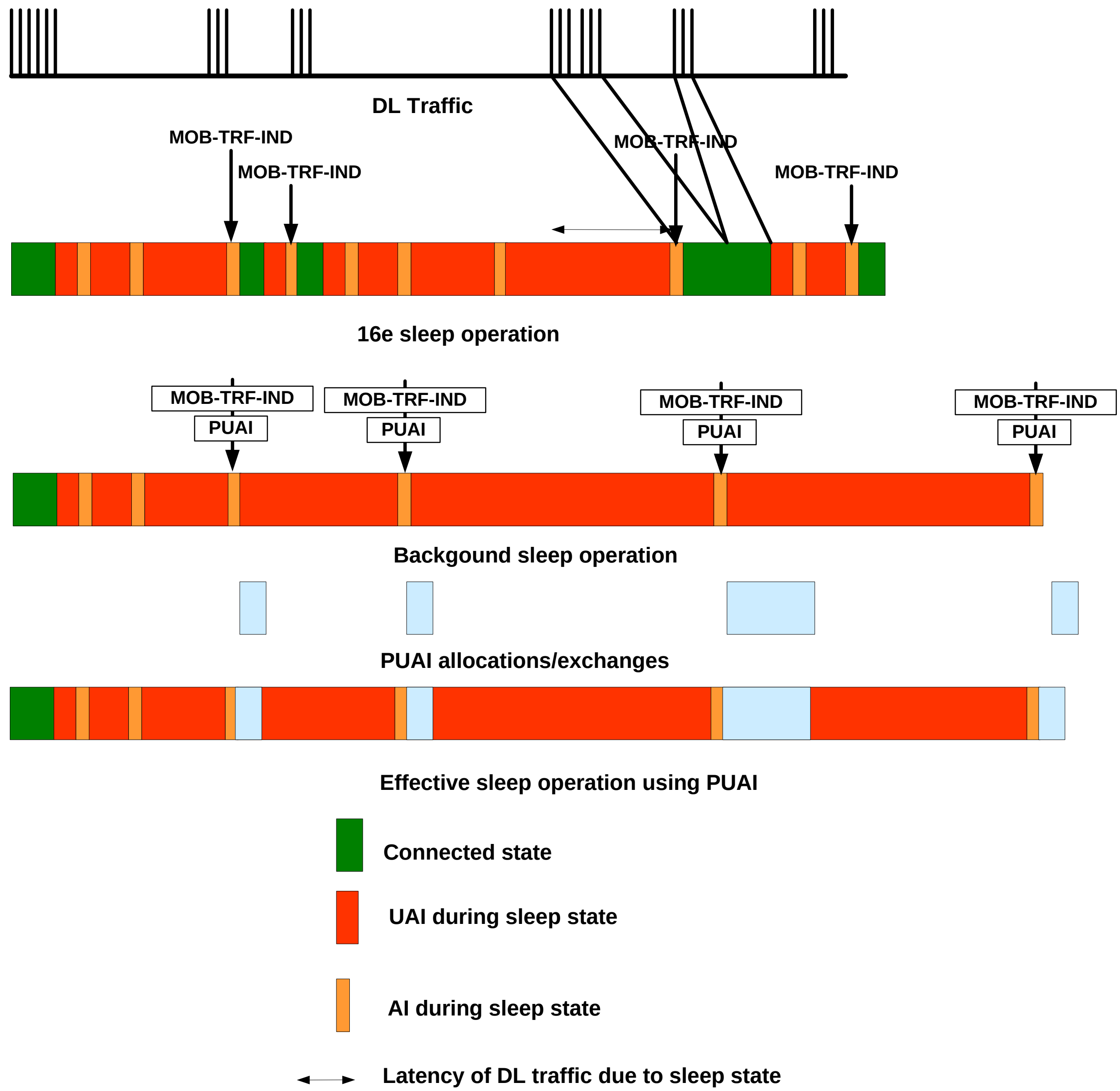

Figure 4: Illustration of sleep operation using PUAI concept.

Operation of PUAI in DL:

In the DL when there is traffic waiting for an SS at the BS, the BS sends a MOB-TRF-IND message during SS's next AI. When MOB-TRF-IND is positive, the BS may use PUAI instead of terminating the sleep mode operation. Towards this, the BS includes a single bit PUAI flag, hereafter referred to as PUAI Flag (PUAIF) in the MOB-TRF-IND for each SS with positive indication. When PUAIF is 1, the BS indicates the duration of the PUAI interval either explicitly or implicitly as described below.

Explicit PUAI duration indication:

In this case the BS informs the PUAI duration using a PUAI message. The PUAI message can be transmitted in one of the following methods.

1. **Using the MOB_TRF-IND message:** BS sends the PUAI message as a part of this MOB_TRF-IND message.
2. **Using a PUAI sub-header/extended sub-header:** BS sends the PUAI message using sub-header or extended sub-header. Note that sub-headers are used in IEEE 802.16e standard [1] to send control information.
3. **As a separate MAC management message:** In the event that the BS does not have the opportunity to piggyback the PUAI message onto other MAC messages using sub-header or extended sub-header, it can send the PUAI message as a separate MAC management message.

The information content of PUAI message used in the above procedures is same and is shown in Table 1. The message contains one bit PUAI Flag that indicate the presence or absence of PUAI. If PUAI Flag is positive, this is followed by PUAI Length.

Table 1: Table showing the PUAI message format.

Syntax	Size	Note
PUAI Flag	1 bit	Indicate the presence or absence of PUAI
If (PUAI Flag) {		
PUAI Duration	M bits	Length of PUAI interval
}		

Implicit PUAI duration indication:

In this case the BS informs the PUAI duration implicitly by informing the SS about the last MAC PDU using one bit flag in the Generic MAC Header (GMH). The PUAI message can be transmitted in one of the following methods. For example, one bit in the GMH can be used to indicate if a particular message is the last one for the SS. The SS learns about the end of PUAI interval when this bit is set to one.

For both explicit and implicit PUAI duration indication, the PUAI start frame number is implicit and starts at the first frame of the unavailability interval immediately following the availability interval in which the PUAI message was exchanged.

Operation of PUAI in UL:

In the UL when there is traffic waiting at the sleep mode SS, the SS sends a bandwidth request message. Upon receiving a bandwidth grant, the SS sends a PUAI message using one of the following methods.

Explicit PUAI duration indication:

In this case the BS informs the PUAI duration using a PUAI message. The PUAI message can be transmitted in one of the following methods.

1. **Using a PUAI sub-header:** SS sends the PUAI message using sub-header or extended sub-header.
2. **As a separate MAC management message:** In the event that the SS does not have the opportunity to piggyback the PUAI message onto other MAC messages using sub-header or extended sub-header, it can send the PUAI message as a separate MAC management message.

The information content of PUAI message used in the above procedures is same as the PUAI message used in the DL and is shown in Table 1.

Implicit PUAI duration indication:

In this case the SS informs the PUAI duration implicitly by informing the BS about the last MAC PDU using one bit flag in the Generic MAC Header (GMH). For example, one bit in the GMH can be used to indicate if a particular message is the last one by the SS. The SS may get back to sleep after sending a message with positive indication in this bit.

For both explicit and implicit PUAI duration indication, the PUAI start frame number is implicit and starts at the first frame of the unavailability interval immediately following the availability interval in which the PUAI message was exchanged.

2.2 **Adapting the sleep mode operation to the dynamic traffic pattern**

Currently, the 802.16e standard requires several messages to attempt a change in the sleep cycle in order to adapt to changes in traffic activity. To change an existing PSC of type II for example, the MS is required to send a Mob-SLP-REQ message [1] to first actively de-activate the PSC and then send another message to re-activate another PSC class. This message exchange is costly both in terms of signaling overhead as well as the latency required to effect the change. As a result, sleep mode as described in 802.16e standard cannot take advantage of short changes in traffic activity. This procedure for changing the sleep activity is similar for PSC type I except that it does not require an explicit message to de-activate an existing AI/UAI pattern. In this contribution, we propose a scheme whereby the MS is able to take advantage of swift changes in traffic activity.

This can be enabled by pre-defining a set of AI/UAI patterns and then sending using either an implicit (timer-based) or explicit (messaging based) mechanism, whichever proves to be more appropriate.

Figure 5 shows an example case of using the concept of switching sleep patterns. In this figure, the traffic, towards the right of the figure has become more frequent. To accommodate this type of traffic, it might be better to switch from a binary exponentially increasing UAI to a fixed UAI of shorter duration, thus reducing overall latency. During each AI interval, we can utilize the always-in sleep concept as explained above to increase the length of the AI interval.

To achieve a quick change in sleep patterns, we propose defining a pre-defined set of sleep patterns which takes into account the services that the MS has access to and their Quality of service. The number of such patterns per MS can be restricted to 8 (3 bits) as opposed to 6 bits used in the current PSC_ID.

Reduce # of PSCs per MS to 8, use 3 bits instead of 6 bits (for a PSC_ID).

As an example, sleep cycles can be configured as follows, using 3 bits:

000 – Fixed sleep cycle : Short AI interval, Short UAI interval

001 – Fixed sleep cycle : Short AI interval, Long UAI interval

010 – Fixed sleep cycle : Long AI interval, Long UAI interval

011 – Binary Exp. sleep cycle: Short AI interval, Short UAI interval, Short Final UAI

100 – Binary Exp. cycle : Short AI interval, Long UAI interval, Long Final UAI

101 – Reserved

110 – Reserved

111 – Reserved

The definition for short and long intervals can be determined by the MS and the Bs.

Sleep cycles can be changed either implicitly using a timer-based mechanism or explicitly using a signaling message. In the implicit mechanism, the BS and the SS may agree on some kind of timer-based trigger mechanism to effect a change in the sleep cycle. For example, the BS and SS may agree that when connections belonging to ertPS type of service class are active, then if there is no traffic activity on both UL and DL for, say x ms, then the sleep cycle will shift to pattern number 1.

Or they can use an explicit mechanism to change the sleep cycle. The messages can be sent in a similar format as described in section 2.1. An example message format can look as shown in Table 3.

Dynamic Sleep change operation	1 bit	0 - Change PSC to one of the pre-defined configurations 1 – Change PSC and modify sleep parameters to newly defined parameters

If (Operation == 1)
{
Specify sleep cycle
Start Frame Offset
}
	7 bits	3 bits – Sleep cycle
		4 bits – Start Sleep Frame Offset

If (Operation == 2)
{
PSC type
AI interval
UAI interval
Final UAI interval
}
	5 bytes	3 bits – Reserved
		4 bits – Start Sleep Frame Offset
		8 bits – Initial Sleep window
		8 bits – Listen window
		10 bits – Final sleep window base
		3 bits – Final sleep window exponent

Table 3: Dynamic sleep switching message.

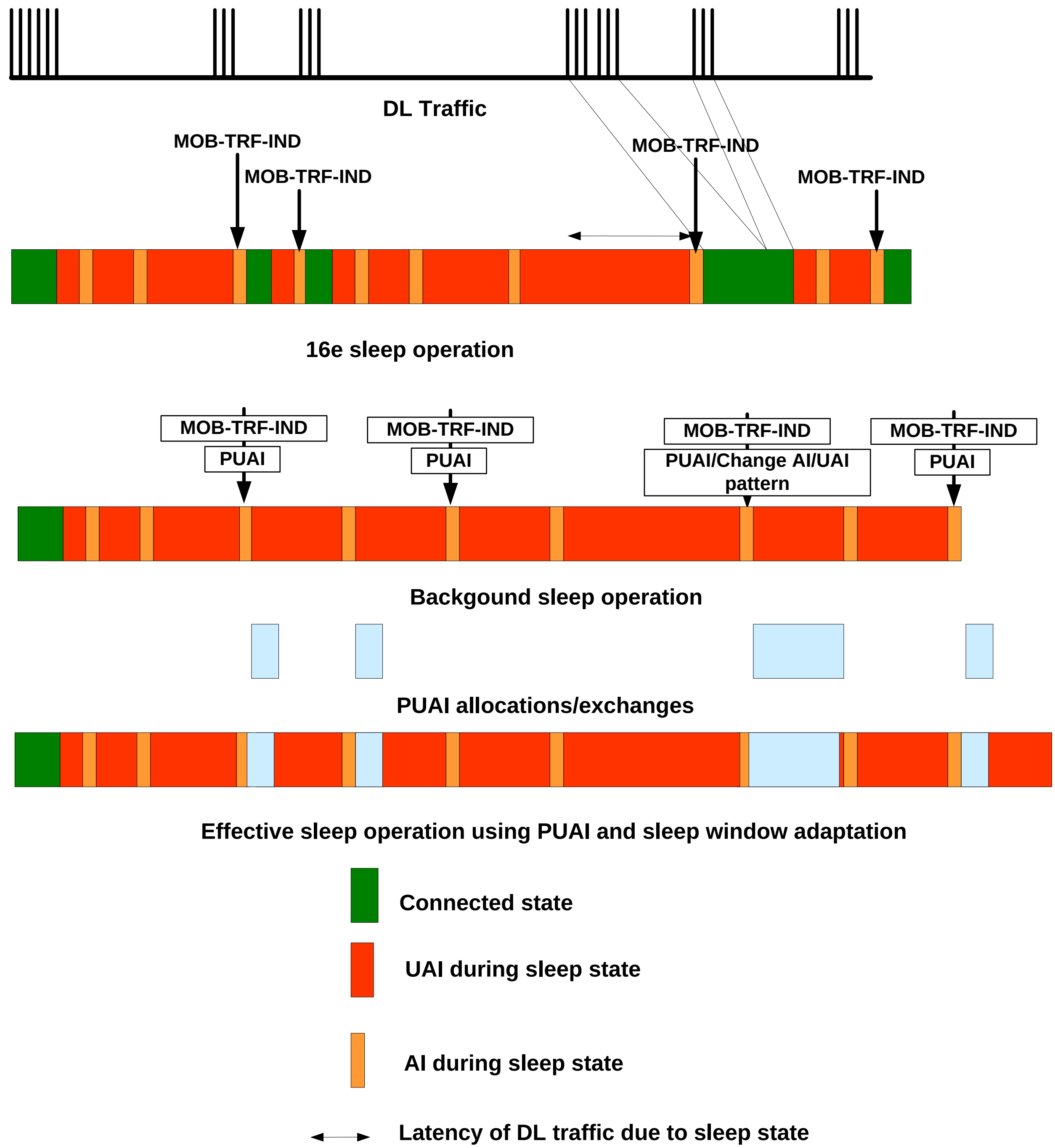

Figure 5: Illustration of proposed PUAI concept and the concept of changing the sleep window to adjust to dynamic traffic pattern

Advantages of using Dynamic Sleep Switching

- Minimized signaling overhead in the number of bytes through
  - Reduction of repeated de-activation/activation of PSC

  - Use of newly proposed shorter sub-header or extended sub-header or using UL control channel message instead of larger messages
- Increased energy savings through faster adaptation to traffic activity
- Enable greater flexibility to define/modify MS sleep cycle to achieve the above.

3. Proposed Sleep Mode Design Considerations

This contribution proposes methodologies to address the design considerations discussed in Section 2.

The use of PUAI is proposed to enable a sleep mode SS to send and/or receive traffic without terminating its sleep mode operation. The methods to implement the PUAI concept are described in Section 2.1.

Adaptation of sleep mode operation to dynamic traffic pattern is proposed by changing the UAI interval of the background sleep operation.

4. Simulation Results

The following simulation results were obtained using the OPNET simulator. The traffic simulated here is BE type of traffic which follows an on/off traffic pattern similar to what is observed in HTTP, but this scenario we only simulated DL traffic since typically UL traffic is minimal. This scenario simulates Ms-initiated Sleep mode triggered after 20 ms of observed inactivity. The start frame of sleep duty cycle is 10 frames from when the MS first initiates the Mob-SLP-REQ message. The length of time simulated is shown in table 4.

Table 4: Simulation details

Total simulation time	15 minutes
% of Total simulation time data traffic exchanged	1.3 %

Figure 6 shows the impact of traffic activity on the sleep duty cycle using the current 802.16e standard operation. As can be seen from the figure, during the AI interval, the BS on observing DL traffic for the SS sends a MOB_TRF-IND message which then de-activates the existing PSC and returns the SS into connected mode. After a certain period of inactivity (in this case 20ms), the SS triggers a new round of Mob-SLP-REQ/RSP messages and the sleep cycle resumes again after a period of about 15 frames of no activity. The sleep cycle again resumes the sleep window from its original size of 2 frames and then starts to increase exponentially towards the maximum size; in this case it is 256 frames. This process repeats the entire length of the simulation duration. The relevant metrics are given in the table 5 below.

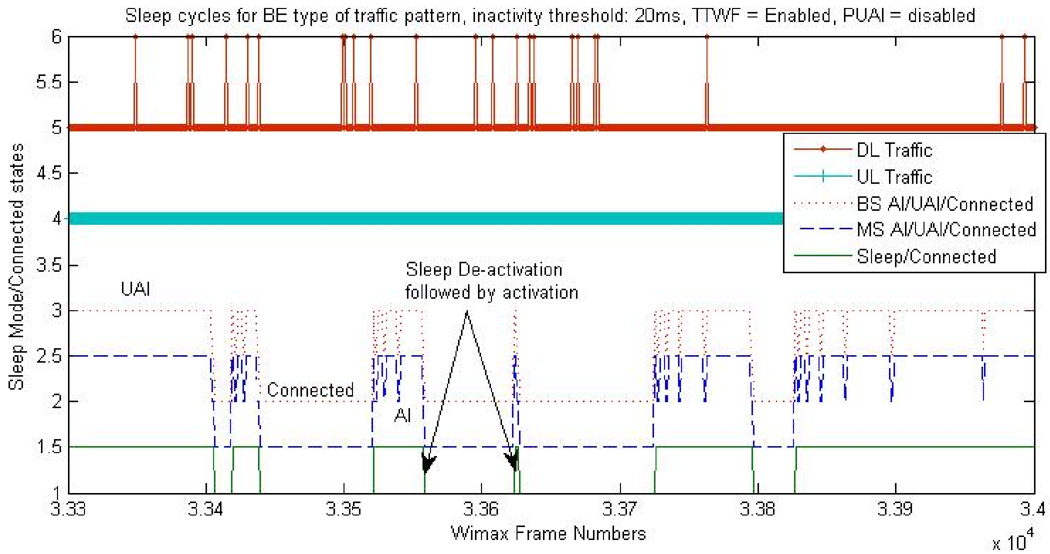

Figure 6: DL BE traffic with 802.16e operation

In Figure 7, the same traffic is simulated with the same sleep trigger algorithm, but with the always-in-sleep concept enabled, the MOB_TRF-IND message is used as before, except that we add another byte to it to include the message to remain on for the next window. As can be observed from figure 7, when the BS receives DL traffic, it is buffered as before until the next Availability interval comes around. At that point, instead of de-activating the sleep mode, the AI is extended by an arbitrary number (a more intelligent algorithm can be used to determine this length, but is out of scope here) of frames. Here this number is 20. After this period, the MS returns to its original sleep cycle as shown in figure 7. Thus, the MS spends greater amount of time in the unavailability interval than in the previous scenario as can be seen from the results in table 5.

From Table 5, the benefits of using the always-in-sleep concept are immediately clear. In table 5, we observe higher number of MOB_TRF-IND messages for the always-in-sleep mode operation. This is because in this particular simulation scenario, the sleep window was always set to what it had been before it had been interrupted, which was the maximum size less the number of frames taken out for the PUAI interval. This increased the average latency of packets buffered and also increased the total number of MOB_TRF-IND messages as it increased the number of packets being buffered. However, both these numbers can be further reduced by using different PUAI interval times and applying the dynamic switching concept whereby the length of the UAI interval is set to a different value depending upon traffic activity.

We also need to take into account the fact that in this simulation scenario, neither the message losses for the entire activation/de-activation operation nor the latency introduced due to this exchange were taken into account and thus are probably lower than what would be actually observed.

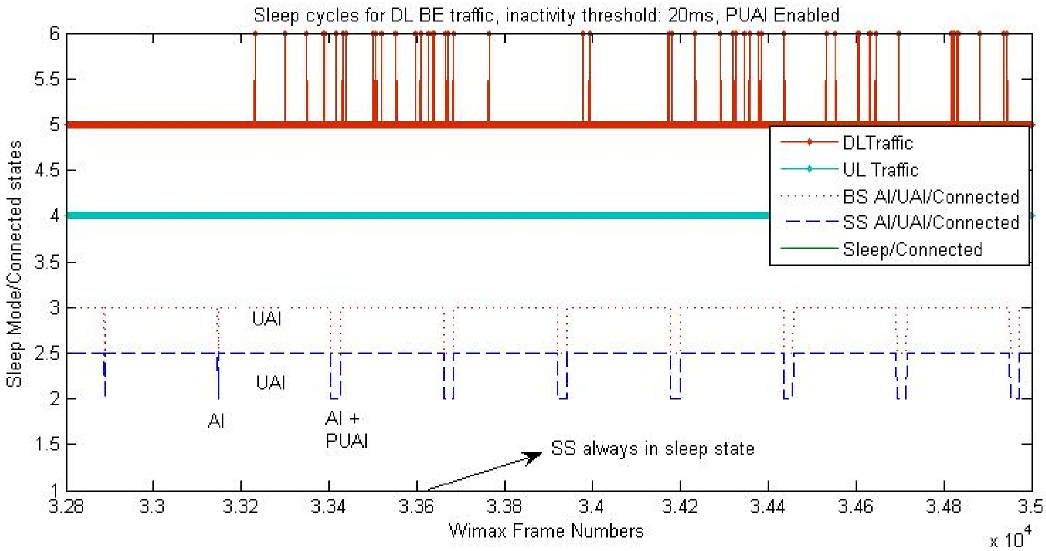

Figure 7: DL BE traffic with proposed Always-in-Sleep concept

Metrics		**802.16e operation, TIR = 1, TTWF Enabled**	**Always-in-Sleep concept**	**Total incremental gain**
Total MAC messaging overhead	PSC Activation/ De-activation overhead	680 * 9 bytes (see note 1)	0	54.32 %
	MOB_TRF-IND message overhead	680 * 2 bytes (see note 2)	1139 * 3 bytes (see note 3)	
% Total Time spent by MS in Unavailability interval		69.70%	91.06 %	21.36%

Table 5: Simulation Metrics Comparison between proposed and current 802.16e standard for sleep mode

Notes:

1. To take into the account the least possible overhead, we assume that the BS sends a DL Extended sub-header message on detection of inactivity after a few frames. This message takes (6 + 3 = 9 bytes)

2. MOB_TRF-IND message can consume up to 7 bytes. But since this is amortized for 32 SSs, we assume a per SS overhead of only 2 bytes, assuming that about 8 out of 32 SS are in sleep mode and require a MOB_TRF-IND message in the same frame.
3. Assuming 1 extra byte to indicate length of PUAI interval.

5. Proposed Text for SDD

Insert the following text into Sleep Mode Operation sub-clause (i.e. Chapter xx in [3]):

------------------------------- Text Start ---

x. x.x.x Sleep Mode Operation

802.16m provides a framework for dynamically adjusting sleep patterns (i.e. duration of sleep and listening intervals) based on changing traffic patterns. MS can send and receive transport data and management messages without deactivating the power save pattern. This power saving framework uses efficient messaging that enables maximum MS power saving and reduces the air-link resource usage associated with signaling related to sleep mode operation.

------------------------------- Text End ---

6. References

[1] IEEE Std. 802.16e-2005, IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, and P802.16Rev2/D3 (February 2008).

[2] WiMAX Forum™ Mobile System Profile, Release 1.0 Approved Specification (Revision 1.4.0: 2007-05-02), http://www.wimaxforum.org/technology/documents.

[3] IEEE 802.16m-08/003r1, “The Draft IEEE 802.16m System Description Document”