PERFORMANCE OPTIMIZATION OF THE INITIALIZATION PROCESS OF IEEE 802.16 MESH NETWORKS

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ABSTRACT

The IEEE 802.16-2004 standard defines a medium access control (MAC) layer for a mesh network topology. In these networks, wide scale power outages can cause serious disruptions to digital services when centralized scheduling is used. This results in very long service recovery times for all mesh nodes. In this paper we propose a new recovery scheme and study the performance of the initialization process due to service disruption of IEEE 802.16-2004 mesh networks. We implemented an OPNET simulation model of the scheme. Results show that the recovery times obtained with the proposed scheme can be reduced by up to 98% compared with the default mechanism.

Index Terms— Performance Analysis, Mesh Networks.

1. INTRODUCTION

The IEEE 802.16 mesh protocol [1] defines two kinds of scheduling mechanisms: distributed and centralized. In the former, a mesh subscriber station (MSS) also termed as a node, competes for channel access using a pseudo-random election algorithm based on the scheduling information about its two-hop neighbors. In addition bandwidth reservation for data transmission is performed using a request-grant-confirm three-way handshaking procedure. In the latter, the mesh base station (MBS) works like a head end and receives all bandwidth requests from all MSSs within a certain hop range as well as grant resources for each node. Because all control and data messages need to pass through the MBS, the scheduling scheme is simple, however the connection setup delay is long [2-3]. Using centralized scheduling, service disruption events such as large scale power outages can seriously affect the system´s performance. Upon such events, all link connections between the MBS and nodes are terminated.

Most studies found in the literature focus on routing, performance analysis and optimization issues of centralized and distributed schedulers. However, as far as we are concerned, only a few works discuss the performance of the network entry process of IEEE 802.16 mesh networks.

In [4] the authors presented a load-aware entry scheme that allows new nodes entering the network to properly sense the load and choose the MBS with the lowest one.

In [5] the authors presented a performance optimization of the network entry and link establishment process, where they found that about 70% of the network configuration (MSH-NCFG) messages exchanged during the initialization process is successful, but this percentage can be extended to 93% by minimizing the effects of hidden terminals.

Our work, however, is rather different from previous works. In this paper, we study the performance of the initialization process after service disruption in IEEE 802.16 mesh networks, where the successful rate of MSH-NCFG and network entry (MSH-NENT) messages is much lower than the 70% reported in [5], thus new allocation schemes for those messages are needed in order to reduce the recovery time. In this paper we propose a new scheduling control scheme that reduces the recovery time up to 98% compared with the default scheme defined in the standard. In order to study the performance of the MAC protocol of such mesh networks, we have developed an event driven simulation model based on the OPNET simulation package.

This paper is structured as follows. Section 2 presents an overview of the relevant parts of the IEEE 802.16 mesh protocol. Section 3 derives the proposed control scheme. In Section 4 we present the simulation model. Section 5 presents the performance analysis of the initialization process of the mesh protocol comparing the proposed scheme with the default mechanism defined in [1]. We conclude the paper in Section 6.

2. IEEE 802.16 MESH TOPOLOGY

The centralized and the distributed scheduling modes use an entry process that is described in [1] section 6.3.9.14. Fig. 1 summarizes a complete message exchange of centralized and distributed scheduling. In the centralized scheme, node X and the MBS node act as the candidate node and the sponsor node, respectively. Once node X is configured, it

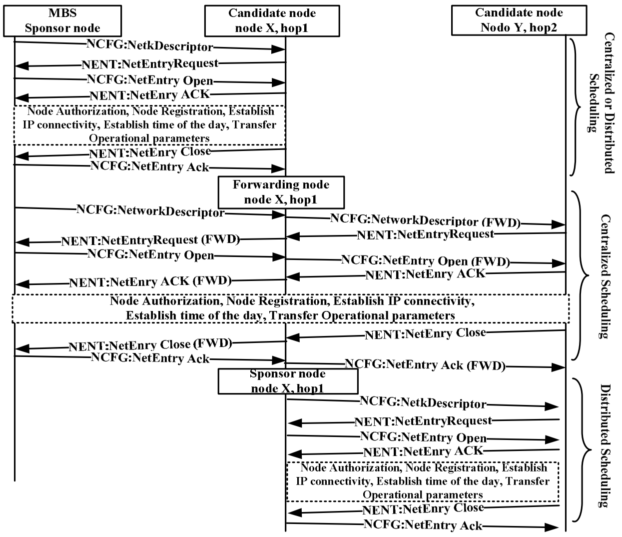


Fig.1. Signaling of the initialization process.

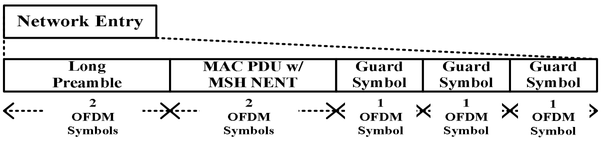
becomes a forwarding node so that other nodes such as node Y can be configured using the initialization process as defined in [1]. In this particular case, the MBS still remains as the sponsor node and node Y becomes the new candidate node.

In the distributed scheme, node X and the MBS node act as the candidate node and the sponsor node, respectively. However, in the distributed scheme when node X is configured, it becomes a sponsor node, which can directly configure other nodes such as node Y. In the following sections we focus on the centralized scheme which demands much more network control signaling at the MBS.

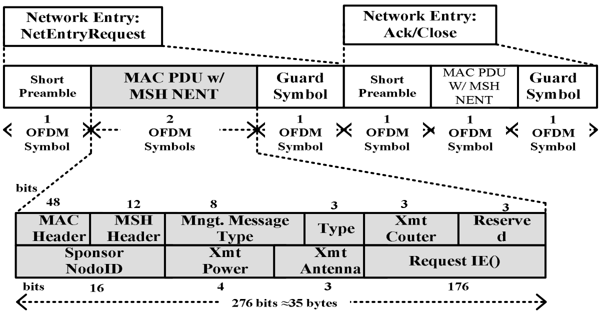
3. PROPOSED SCHEDULING CONTROL PROCESS

In the event of a power outage, a candidate node needs first to synchronize with the mesh network. Then, whenever the candidate node receives a MSH-NCFG:NetDescriptor message with sponsored MAC address = 0, the candidate node should transmit its first message (MSH-NENT: NetEntryRequest) to the sponsoring node or the MBS using contention-based access, in the following MSH-NENT Transmission Opportunity (TxOp). The other messages (MSH-NENT: NetEntryAck, and MSH-NENT: NetEntryClose) should be transmitted immediately using the following MSH-NENT TxOp, after the candidate node receives its associated MSH-NCFG messages, as shown in Fig 1. Therefore, the real problem is that in a power outage, tens of nodes would contend for those MSH-NENT TxOps, resulting in a poor initialization system performance, due to a large number of collisions.

The initialization performance is even worse if the configuration parameters such as *XmtHoldoffExponent* (XHE), *NextXmtMx* (NXM), *Frame Duration* (F_D), and *Scheduling Frames* (S_f) are not optimized.



(a) Default Network Entry frame structure



(b) Proposed Network Entry frame structure

Fig. 2. Network entry frame structures.

Since the standard [1] defines only one MSH-NENT TxOp of 7 OFDM symbols every S_f frames, as illustrated in Fig. 2a, we propose the following frame structure to optimize this region.

In our framing scheme, after a power outage, we propose to use short preambles for the transmission of MSH_NENT messages. This can be possible by simply setting the Short Preamble Flag to 1 of the *Nbr Logical IE* Information structure included in the MSH-NCFG message (with sponsored MAC address = 0), as indicated in [1], Section 8.3.3.6.

We also propose to use one Guard Symbol. This is possible because the standard defines that the transition gap for all Wireless MAN-OFDM system profiles should be ≤ 100 μs (Section 12.3, [1]). In Table 1, for all channel bandwidths supported in the mesh mode, the OFDM symbol duration (T_s) is less than 100μs. In addition, all other frames in the mesh mode (i.e. Centralized Configuration, Centralized Scheduling and Distributed Scheduling) use one Guard Symbol. Therefore, using one symbol for this transition gap is within the operational values.

By using short preambles and considering one Guard Symbol we can, in fact, transmit two MSH-NENT messages in one NENT TxOp as illustrated in Fig. 2b. In the first 4 OFDM symbols we can transmit one MSH-NENT message with Type = 0x02: NetEntryRequest.

TABLE 1. NENT CHANNEL UTILIZATION.

		NENT TxOps	1	2	4	1	2	4	1	2	4
BW	T_s	S_f	10	10	10	8	8	8	4	4	4
[MHz]	[μs]	No.OFDM [syb/frame]	γ [%]	γ [%]	γ [%]	γ [%]	γ [%]	γ [%]	γ [%]	γ [%]	γ [%]
3	93	119	0.6	1.2	2.4	0.7	1.5	2.9	1.5	2.9	5.9
3.5	80	138	0.5	1.0	2.0	0.6	1.3	2.5	1.3	2.5	5.1
5.5	51	219	0.3	0.6	1.3	0.4	0.8	1.6	0.8	1.6	3.2
7	40	277	0.3	0.5	1.0	0.3	0.6	1.3	0.6	1.3	2.5
10	28	400	0.2	0.4	0.7	0.2	0.4	0.9	0.4	0.9	1.8
25.6	11	1024	0.1	0.1	0.3	0.1	0.2	0.3	0.2	0.3	0.7

However, in the last 3 OFDM symbols we can only transmit either a MSH-NENT message with Type = 0x01: NetEntryAck or a MSH-NENT message with Type = 0x03: NetEntryClose. Thus, we just need to verify that the MAC PDU w/NENT fits in two OFDM symbols for the NetEntryRequest option and one symbol for the NetEntryAck/NetEntryClose options.

In Table 2 we show the channel coding per modulation supported in the mesh mode. However, the transmission of control subframes (such as MSH-NENT and MSH-NCFG) must be sent using the mandatory coding scheme (QPSK with ½ overall coding rate). The uncoded frame size in bytes that can be transmitted in one OFDM symbol is given by $N_{used}*m*CR/8$, where N_{used} is the number of data subcarriers. Then, the MAC PDU w/MSH NENT:NetEntry Request (Figure 2.b) requires 35 bytes which can be transmitted using two OFDM symbols with the mandatory modulation scheme. The frame structure of the MAC PDU w/MSH NENT:NetEntryAck/NetEntryClose is the same as the MAC PDU w/MSH NENT:NetEntryRequest without the Request IE field. This results in a frame of 13 bytes which can be transmitted using one OFDM symbol with the mandatory modulation scheme.

In addition, we further enhance our proposed framing scheme by using 3 bits of the *reserved* field in the MSH-NCFG message format. With these 3 bits we propose to add the following parameters:

- ***NetEntry Power Outage Flag, "NetPwrOut",*** (1 bit).
  0: Indicates normal operation, 1: indicates the nodes to enter the network after a power outage.
- ***NetEntry Transmission Opportunities, "NENT"*** (2 bits):
  0: 1 TxOp is required when *NetPwrOut* =0. (normal operation)
  1: 2 TxOp are required when *NetPwrOut* =1
  2: 3 TxOp are required when *NetPwrOut* =1.
  3: 4 TxOp are required when *NetPwrOut* =1.

When the NetPwrOut flag is set to 1, indicates that our proposed framing structure, as described in Fig. 2.b, should be employed in the initialization process after a power outage.

By using the proposed framing structure and the new parameters the system performance, during the initialization process, is considerably improved, as we will demonstrate in the following sections. We just need to explain how the scheduling of control messages is carried out.

In order to transmit the NCFG messages, the standard [1] defines that after the transmission of a NCFG message at the *Next Transmission Time* (NXT), as shown in Fig. 3, a node "X" must defer its transmission by a period of ESXT = 2^{XHE+4} TxOps, before contending again, where ESXT is the *Earliest Subsequent Transmission Time*. Once the ESXT period of a node X has elapsed, such node should contend in every TxOp during the NXT interval: $2^{XHE}NXM<NXTI\leq 2^{XHE}(NXM+1)$, using an election procedure.

TABLE 2. CHANNEL CODING PER MODULATION.

Modulation	Bits per symbol (m)	Uncoded block size [bytes]	Coded block size [bytes]	Overall coding rate (CR)
QPSK	2	24	48	1/2
QPSK	2	36	48	3/4
16-QAM	4	48	96	1/2
16-QAM	4	72	96	3/4
64-QAM	6	96	144	2/3
64-QAM	6	108	144	3/4

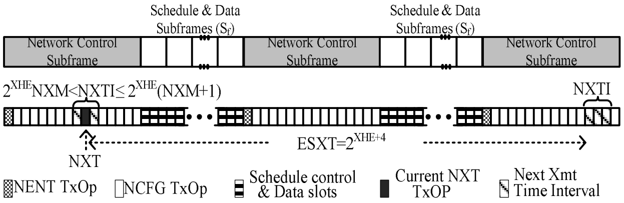
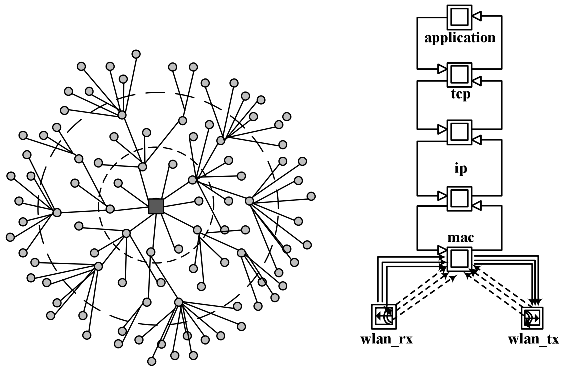
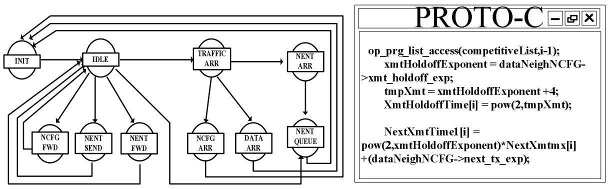


Fig. 3. Network control access.



(a) Network model (b) Node model



```
  op_prg_list_access(competitiveList,i-1);
      xmtHoldoffExponent = dataNeighNCFG-
>xmt_holdoff_exp;
      tmpXmt = xmtHoldoffExponent +4;
      XmtHoldoffTime[i] = pow(2,tmpXmt);

      NextXmtTime1[i] =
pow(2,xmtHoldoffExponent)*NextXmtmx[i]
+(dataNeighNCFG->next_tx_exp);
```

(c) Finite State Machine diagram (d) Proto-C

Fig. 4. Simulation model.

4. SIMULATION MODEL

We implemented a detailed simulation model of the IEEE 802.16 MAC protocol network entry using the OPNET Package v. 14.5. A hierarchical design was used and it is shown in Fig. 4. At the top level of the network topology, the network components, for example the MBS and MSS, along with their connectivity are shown in Fig 4a. This image shows the tree generated after the simulation. The next level, Fig. 4b, defines the functionality of a MSS in terms of components such as traffic sources, MAC interfaces, etc. The operation of each component is defined by a state machine (an example of which is shown in Fig. 4c). The actions of a component at a particular state are defined in Proto-C code such as that in Fig. 4d.

TABLE 3. SIMULATION PARAMETERS.

Parameter	Value
Frame Duration T_F	10ms
OFDM symbol / frame	1024
OFDM symbol / slot	4
Opportunity transmission (TxOp) time / slot	68.359 µs
Bandwidth	25.6 MHz
MSS Transmission Power	0.3 W
Data rate	59 Mbps
Distance of SS to the BS	0.1 - 5 km

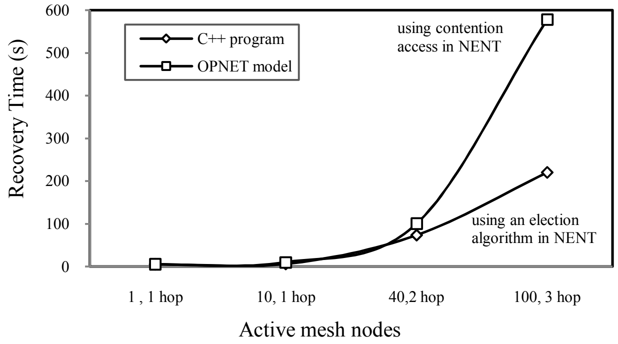
This approach allows modifications to be applied to the operation of the IEEE 802.16 protocol and different optimizations and enhancements can be tested. This simulation model carries out the initialization process of candidate nodes as shown in Fig. 1, using contention access for NENT messages, and using the election algorithm (as defined in [1], p. 345) for NCFG messages. In addition, we employed the transmission timing of control messages as suggested in [6]. To validate the results we also implemented a C++ program where both the NENT and NCFG messages are sent using the election algorithm defined in IEEE 802.16-2004.

5. PERFORMANCE EVALUATION

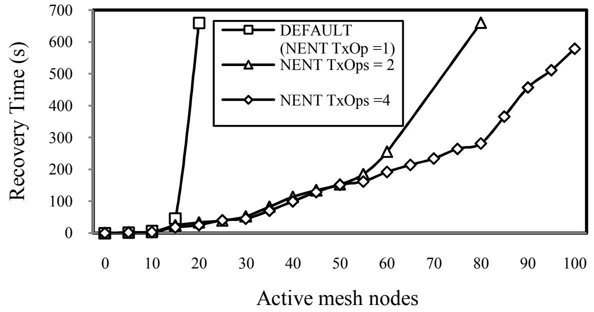
For the performance analysis we employed a mesh network with 100 nodes, where 10 of these nodes (node1 to node10) are 1 hop from the MBS, 30 nodes (node11 to node 40) are 2 hops from the MBS and 60 nodes (node 41 to node 100) are 3 hops from the MBS as depicted in Fig. 4a. The parameters used in the C++ program and in the simulation model are as indicated in Table 3.

In Fig. 5a, we present the maximum delay that it takes the mesh network to recover after a power outage, using our framing structure with 4 NENT TxOps per Network Control Subframe (***NetPwrOut=1, NENT =0x3).*** Both models (i.e., simulation and the C++ program) present nearly the same recovery delays for nodes that are up to 2 hops from the MBS (node 1 to node 40). This behavior is to be expected since the number of collisions reported in the simulation model is marginal and does not affect the recovery delay. However, nodes that are 3 hops from the MBS trigger a higher number of collisions since every message sent by nodes from 41 to 100 should be forwarded twice to reach the MBS, provoking an increased number of collisions in the NENT region when the simulation model is used. Compared with the C++ program, the recovery delay given by the simulation model could be reduced from 580 to 220 seconds when an election algorithm is also used for the transmission of NENT messages.

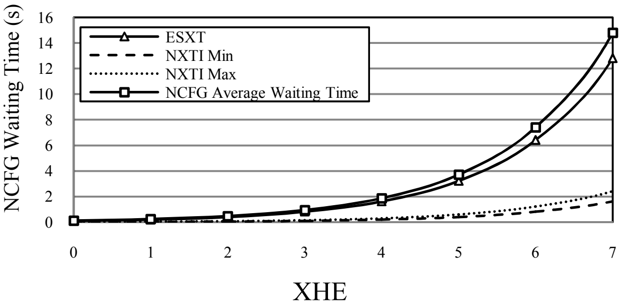
In Fig. 5b we present the recovery delay using only the simulation model. We compare this delay using the default mechanism defined in the standard with our proposed framing structure. The default mechanism presents a very large recovery delay, due to a great number of collisions of NENT



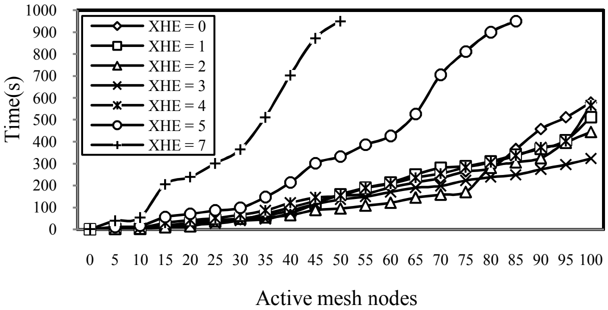
(a) Recovery delay using the C++ Program and the simualtion model, NENT TxOps =4, XHE = 0.



(b) Recovery delay using the simulation model, the default mechanism and the proposed framing structure, XHE = 0.



(c) Average waiting time between NCFG mesages, NENT TxOps = 4, L=10.



(d) Recovery delay using the simulation model, and different XmtHoldoffExponent values, NENT TxOps = 4, L =10.

Fig. 5. Recover delay of the initialization process for different network configurations.

messages, since only one NENT TxOp is allocated every (S_f*T_D =) 100 ms. For instance, using a network size of 20 nodes, the recovery delay reported by the simulation model was 660s. By using our proposed framing structure, with 2 and 4 NENT TxOps per Network Control subframe we can considerably decrease the network recovery time to 33 and 13 seconds respectively. This results in a maximum recovery time reduction up to 98% (≈[1-13/660]*100).

However, having more NENT TxOps in the Network Control subframe increases the signaling overhead (γ). In Table 1 we showed this overhead for different channel bandwidths suggested by the standard [1] for the mesh protocol. For example, for a channel bandwidth of 25.6 MHz as used in the simulation model, the NENT overhead results in approximately 0.3% (≈100*NENT TxOps*7/1024*S_f) of the channel utilization when NENT TxOps =4. This overhead, in the worst case scenario, becomes 5.9% of the channel utilization when S_f = 4, BW = 3MHz and NENT TxOps =4.

In addition, in order to further reduce the recovery time, it is also necessary to optimize the election period for the transmission of NCFG messages, given by NXTI [2^{XHE}NXM+1, 2^{XHE}(NXM+1)]. From the two configurations parameters: XHE and NXM, the former is the one that can modify the election period. For instance, having XHE = 2, results in an election window size of (2^{XHE} =) 4 NCFG TxOps, compared to 127 NCFG TxOps when XHE = 7. By increasing the election window, however we also considerably increase the ESXT. Thus, the average waiting time for the transmission of every NCFG message is given by ESTX + ($NXTI_{Min}$+$NXTI_{Max}$)/2, as shown in Fig. 5.c. Hence, for XHE = 2 and 7, the average waiting times for NCFG messages were of 0.5 and 14.8 seconds respectively, when NENT TxOps = 4 and the number of TxOp per network control subframe (MSH-CTRL-LEN) was set to 10.

Finally, in Fig. 5d we show how the recovery time is affected by XHE. We observe that for large networks, the minimum recovery delay is obtained with XHE = 3. The recovery delay is reduced from 580s obtained with XHE = 0 (see Fig. 5a and 5b), to 322s when XHE = 3, and there are 100 active nodes in the network. For medium size networks (between 20 and 75 nodes), however the optimum performance was obtained with XHE = 2. This is to be expected, because the mean waiting time between NCFG messages is reduced by half. For example, with XHE =2, the mean number of contending nodes per election window is between ($2^{XHE}*N/2^{(XHE+4)}$=)1.25 and 4.6, these users share the same election windows=4 NCFG TxOps when network size (N) ranges from 20 to 75 nodes, respectively. On the contrary, when XHE =3, the same number of contending users per election window (1.25-4.6) share 8 NCFG TxOps every 128 TxOps, compared to 64 TxOps when XHE=2.

6. CONCLUSIONS

This paper studied the recovery mechanism of mesh networks based on the IEEE 802.16-2004 standard after a service disruption. Since the fast recovery of the mesh network is necessary for the provision of digital services, identifying the parameters controlling it and applying new schemes in order to minimize this disruption is important. Herein we introduced a new scheduling control process that optimized the NENT and NCFG region of the network control subframe. With our proposed scheme, the MAC protocol of such mesh networks is capable of providing a timely recovery after a service disruption event.

In order to validate our scheme, we compared our results obtained with an Opnet simulation model with a C++ program. Both models presented nearly the same recovery delays for nodes that were 1 and 2 hops away from the MBS. Finally, by comparing the performance of our proposed scheme with the default mechanism we achieved a recovery time reduction of approximately 98%. Future work will focus on studying the effects of channel errors in our proposed scheme and analyze other configuration parameters such as MSH-CTRL-LEN, F_D, S_f and channel bandwidth.

7. ACKNOWLEDGEMENTS

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