



Improving Energy Saving in Time-Division Multiplexing Passive Optical Networks

This article proposes a time-division multiplexing passive optical network (TDM-PON) architecture in which optical network units (ONUs) enter active mode only when the optical line terminal has traffic to deliver. The authors use a hybrid ONU (H-ONU) equipped with a low-cost, low-energy IEEE 802.15.4 module. This module notifies H-ONUs when they should move from sleep to active mode to receive downstream traffic. The authors show that the proposed solution leads to a significant energy saving while satisfying PON delay requirements.

Access network equipment, such as that used in time-division multiplexing passive optical networks (TDM-PONs), consumes around 70 percent of the overall telecom network energy consumption, but its utilization is less than 15 percent.¹

Sleep mode is the most commonly used energy saving principle for TDM-PONs. Existing energy saving solutions propose that optical network units (ONUs) periodically enter active mode to check for downstream traffic stored in the optical line terminal (OLT) and waiting to be transmitted (see the “Related Work in Energy Saving in TDM-PONs” sidebar). If there is traffic in the OLT, the OLT notifies the ONU using a beacon frame, and the ONU remains in active mode until it receives the traffic. Otherwise, it re-enters sleep

mode by switching off some of its components.

Although this approach clearly helps save energy compared to keeping the ONU in active mode continually, the ONU often fails to receive traffic after processing the OLT beacon, because the OLT doesn’t always have traffic to transmit to that ONU. In these cases, the ONU uselessly expends energy. Therefore, it would be more efficient to keep ONUs in sleep mode unless they have incoming traffic.

In our solution, ONUs only enter active mode when there is downstream traffic in the OLT. We propose a hybrid ONU (H-ONU), which is a standard ONU module equipped with a low-cost, low-energy IEEE 802.15.4 module that powers on the ONU when it needs to receive traffic. Our PON architecture

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Related Work in Energy Saving in TDM-PONs

Several authors propose a three-way handshake between the optical network unit (ONU) and an optical line terminal (OLT) before an ONU moves to sleep mode.^{1–4} In this process, the OLT decides the next sleeping interval (that is, the interbeacon arrival period, T_b) based on the downstream traffic arrival rate and notifies the ONU using a beacon message. The ONU wakes up after T_b . If the OLT has some traffic stored for that ONU, the OLT delivers that traffic. Otherwise, the ONU returns to sleep mode. When an ONU wakes up, it spends energy moving from sleep to active mode, processing the OLT beacon frame already in active mode, receiving traffic, if any, from the OLT, and moving from active to sleep mode.

Therefore, if no downstream traffic is available when the ONU wakes, all of this energy is wasted. This phenomenon can be significant during off-peak traffic hours. Additionally, predicting traffic arrival patterns, which could reduce the number of failed attempts, is a difficult task that leads only to approximate models. Therefore, a considerable probability still exist of failing on the waking-up process.

Finally, because all solutions described in the main text follow a similar approach to saving energy while delivering downstream traffic, we group them together and call them polling solutions because all ONUs periodically wake up to check for available downstream traffic.

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is formed by one or more *coordinator H-ONUs* (CH-ONUs) that periodically receive a beacon frame from the OLT. This beacon frame includes the scheduling of OLT downstream transmissions to all H-ONUs (including CH-ONUs). In particular, it contains those H-ONUs that should enter active mode to receive traffic and the instant at which the traffic will be transmitted to each one. The CH-ONU passes that information to the H-ONUs using a wireless sensor network (WSN) formed by the H-ONUs' IEEE 802.15.4 modules. Each IEEE 802.15.4 module uses this information to decide whether to move its associated ONU module into active mode.

Initially, our solution seems to have a clear drawback – that is, the extra delay imposed by the WSN notification network. However, our solution is highly flexible and can satisfy PON delay requirements while saving a significant amount of energy.

Reducing Energy Consumption in TDM-PONs

Figure 1a shows the H-ONU architecture. The WSN notification network formed by the IEEE 802.15.4 modules indicates which H-ONUs should enter active mode to receive downstream traffic and when. Figure 1b shows our proposed PON with WSN notification network.

PON Operation Using H-ONUs

The OLT selects one (or more) of the H-ONUs to be the CH-ONU. A CH-ONU acts like an ONU in the polling solution. That is, it wakes up after the interbeacon arrival period, T_b , which is decided by the OLT, and receives a beacon frame from the OLT. However, instead of each ONU receiving its own beacon as in the polling solution, we propose a single beacon frame containing information for all H-ONUs attached to the OLT. Information in the OLT beacon includes the list of H-ONUs that should enter active mode to receive traffic, and the instant at which each H-ONU will receive the traffic.

Once a CH-ONU has received and processed an OLT beacon, it uses the WSN notification network to send a WSN notification message (WSN-NM) alerting the other H-ONUs. Each H-ONU uses its IEEE 802.15.4 module to process the message. If some downstream traffic is going to be sent from the OLT to a particular H-ONU, that H-ONU's IEEE 802.15.4 module must fully activate the unit to receive the traffic.

Therefore, unlike the polling solution, our proposal requires that only the CH-ONU wake up to process the OLT beacon in each interbeacon arrival period, T_b , while the remaining H-ONUs use a low-energy IEEE 802.15.4 module (30 mW consumption when the radio transmitter is on, and 30 μ W when it's off²).

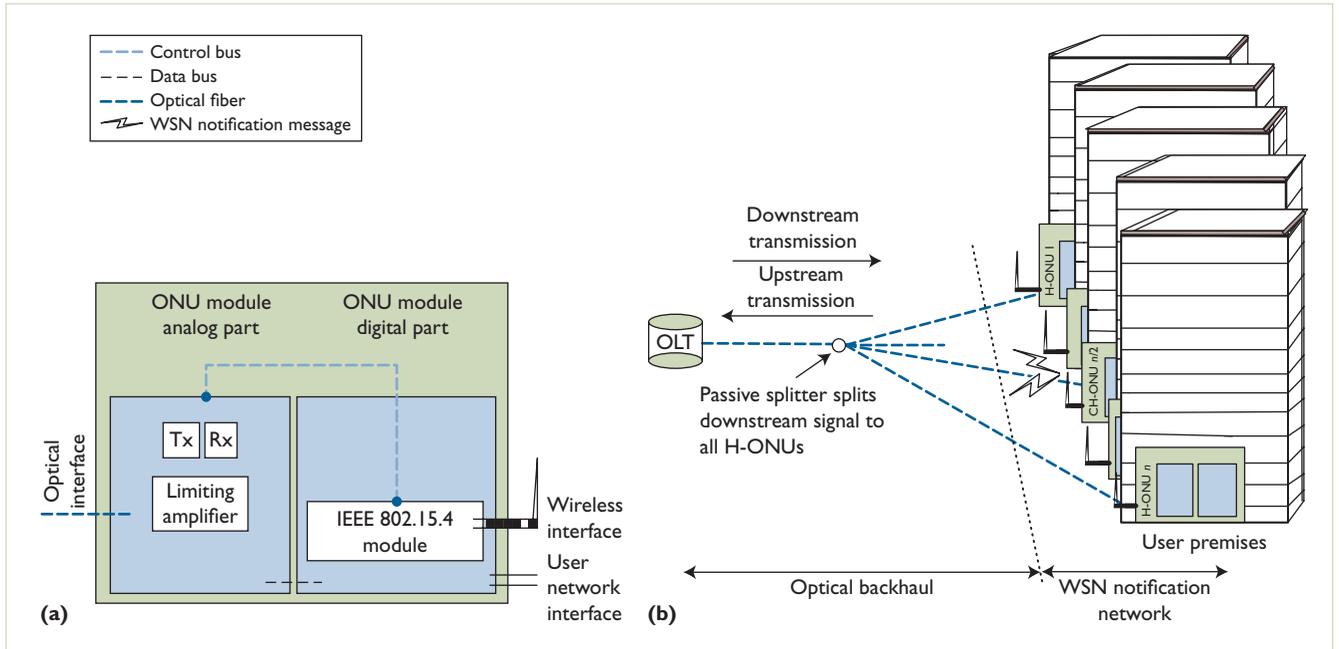


Figure 1. Proposed solution. (a) Hybrid optical network unit (H-ONU) architecture (integration of an ONU and an IEEE 802.15.4 module). (b) H-ONUs forming a PON access network and a WSN notification network.

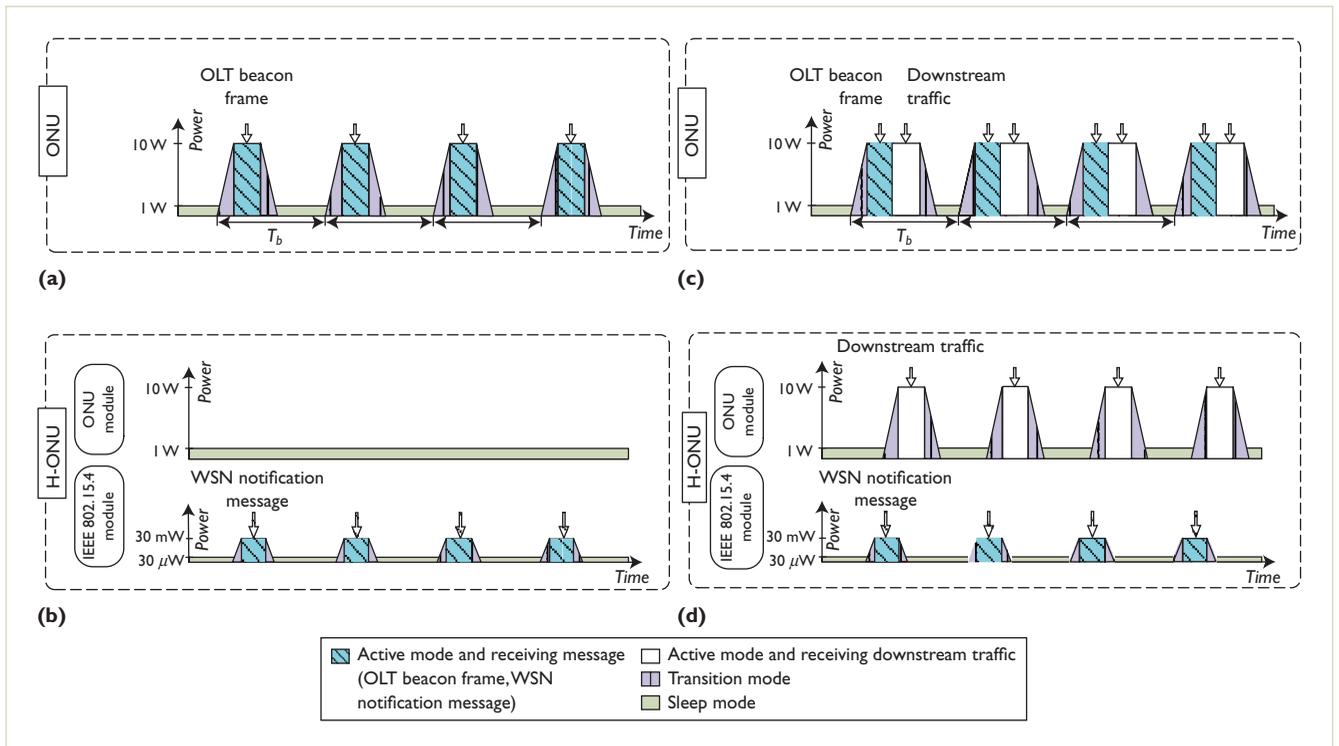


Figure 2. Schematic comparison between polling and the proposed solution: working procedure of (a) an optical network unit (ONU) and (b) a hybrid ONU (H-ONU) when no downstream traffic is available; and working procedure of (c) an ONU and (d) an H-ONU when downstream traffic is available.

Figure 2 compares the two solutions. In each T_b we find two situations from the ONU viewpoint: downstream traffic available at the OLT or

no downstream traffic. This defines an upper and lower bound of energy saving when our solution is adopted. We compute these two bounds later.

Therefore, this solution's clear benefit is that a low-power technology (that is, IEEE 802.15.4) deals with OLT downstream traffic notification. For upstream transmission, if traffic arrives at an H-ONU from the user, the H-ONU wakes up and transmits it during a dedicated upstream transmission slot.

WSN Notification Network Operation

To notify the IEEE 802.15.4 modules of H-ONUs that need to be active for receiving downstream traffic from the OLT, we propose using WSN notification network operational procedures.

WSN-NM. This message uses the frame structure provided by the IEEE 802.15.4 standard with a maximum size of 127 bytes. Using a 9-byte MAC header and an 8-byte routing header (for example, ZigBee routing header size), a CH-ONU can use up to 110 bytes to notify H-ONUs when they have to enter active mode to receive traffic from the OLT.

Our first field is the `notification vector`, which is N bits, where each bit represents one of the H-ONUs attached to the OLT. Then, if bits 1, 3, and 6 are set to "1," it means that those H-ONUs should enter into active mode to receive downstream traffic stored in the OLT.

Note that the OLT can only transmit to one ONU at a time. Therefore, the beacon frame includes a time stamp indicating when each H-ONU should enter in active mode. These time stamps are included in the WSN-NM after the `notification vector` field. The first time stamp will refer to the first bit set to "1" in the `notification vector` field, and so on.

Routing protocol. Our routing protocol is a multihop network with 1 to N communication, where the one CH-ONU communicates with the other H-ONUs. The most suitable solution for routing in the WSN notification network is to create a tree structure to route WSN-NMs from the CH-ONU to all other H-ONUs (similar to ZigBee's tree routing³). Depending on the WSN topology, there will be more or fewer hops from the CH-ONU to the furthest H-ONU. Hence, this solution requires a simple routing protocol based on parent-children forwarding, which lets it easily deploy time-division scheduling to avoid collisions. This would help avoid the reliability problems that usually appear in WSNs where many sensors try to access the medium simultaneously. In addition, IEEE 802.15.4 provides a hop-by-hop acknowledgment mechanism that supports cases of unsuccessful transmission.

Our solution is intended for use in cities where buildings are only some tens of meters apart, a realistic assumption for many urban areas given statistics for the 101 US cities with the highest housing density.⁴ Among these 101 cities, the least densely populated city (Seaside Heights, New Jersey) has an interbuilding distance of 28.7 meters, whereas the most densely populated (Friendship Village, Maryland) reduces this value to 6.7 meters. With this distance value, and accounting for some reference figures for recent sensor nodes (more than 50 m indoor and more than 300 m for outdoor environments⁵), we can make the realistic assumption that in dense cities, one H-ONU can reach one or more H-ONUs within the same OLT using just one hop.

Beacon frame interval. The maximum transmission rate in IEEE 802.15.4 is 250 kilobits per second (kbps). However, in a real experiment, the MAC layer functionality (for example, ACK transmissions and backoff periods) limits the maximum effective data rate to half this speed.⁶ This directly impacts the minimum practical T_b . So, being conservative and considering a frame of maximum size, we conclude that our solution works with beacon intervals greater than 10 milliseconds (ms).

Although using IEEE 802.15.4 for notification reduces ONU energy consumption, an IEEE 802.15.4 WSN brings another challenge – delay in relaying WSN-NMs. Experiments have found that the one-hop delay in an IEEE 802.15.4 network is 6 ms (including ACK confirmation).⁶ Under some unfriendly topologies (for example, straight line), the WSN delay could reach values close to 100 ms, which could be intolerable for some applications. However, our solution is highly flexible and can easily reduce the delay in different topologies by using more CH-ONUs. In this case, each CH-ONU takes control over a subset of H-ONUs forming a cluster (subnetwork). Each CH-ONU is then responsible for notifying the H-ONUs within its cluster.

Performance Estimation and Results

We compared our solution to the polling solution in terms of energy consumption and delay in the PON access network.

Energy Saving

We obtain the energy consumption from the amount of time an ONU stays at different

states: active mode (10 W),⁷ sleep mode (1 W),⁷ and transition mode (2 W).⁸ This latter mode refers to the period in which an ONU goes from sleep to active mode and the other way around. This involves turning on its components and achieving PON synchronization when waking, or turning off components to move into sleep mode. Both transition times last 2 ms.⁷⁻⁹ The time required to receive and process an OLT beacon frame is 1.6 ms.⁷ Finally, the time spent in active mode to receive data traffic depends on how much traffic the OLT sends.

An ONU's energy expenditure in both solutions for one interbeacon arrival period (T_b) depends on whether the OLT contains buffered data to be delivered to that ONU. Therefore, when considering energy saving, we must take two cases into account.

First, if downstream traffic isn't available in OLT, the H-ONUs stay in sleep mode during all T_b time periods (see Figure 2b). However, the polling solution must activate the ONUs to receive the OLT beacon frame (see Figure 2a). Therefore, the extra energy consumption in the polling solution comes from the 1.6 ms required while in active mode to process the OLT beacon frame, and the time to move from sleep mode to active mode and the other way around, which is 4 ms under a power consumption of 2 W. Obviously, the energy saving is higher in this case than when downstream traffic is available. Therefore, if no downstream traffic is available in any single T_b for an ONU in a given observation period, our solution would generate the maximum amount of energy saving in this case compared to the polling approach (that is, this would be the energy saving upper bound for our solution in comparison to the polling approach).

Second, if downstream traffic is available in the OLT, both H-ONUs and standard ONUs must enter active mode to receive traffic. The only difference is that the polling solution requires extra time in active mode to process the OLT beacon frame, which the H-ONUs in our solution avoid because they only enter active mode to receive traffic (see Figure 2d). In this case, the polling solution uses an additional 1.6 ms in active mode than our proposed solution, except for the CH-ONU, which uses the 1.6 ms to process the OLT beacon frame. If this occurred in every T_b period during a given observation period, it would establish an energy saving lower bound because the energy consumption difference

between our solution and the polling approach would be the lowest possible in that period.

To accurately measure the energy expenditure in our solution, we need to account for the energy spent by the WSN (E_{WSN}) and CH-ONUs.

Each H-ONU is attached with an IEEE 802.15.4 module that needs to turn the radio on (30 mW power consumption) to receive the WSN-NM, and, in some cases (when the H-ONU isn't a leaf), to forward that message to the next hop H-ONU in the routing tree. It takes 6 ms for an IEEE 802.15.4 module to transmit a message and receive an ACK;⁶ thus, in the worst case, the IEEE 802.15.4 module will be on for 12 ms (6 ms each for receiving and forwarding) per T_b . The energy used when the radio transceiver is off is negligible because the power consumption in this state is only 30 μW .² Therefore, if we assume that we have as many sensor nodes as ONUs per OLT, we can easily compute the E_{WSN} . Finally, it must be noted that an active sensor consumes 300 times less energy than an ONU in active mode.

A CH-ONU consumes the same amount of energy as an ONU in the polling solution. Therefore, the more CH-ONUs our solution uses, the less energy we save compared to the polling solution (see Figure 3a).

We can measure energy savings in both solutions. Figure 3a shows the lower and upper bounds of energy savings provided by our solution compared to the polling approach in a single T_b period. As the figure shows, the energy savings when using a single CH-ONU goes from 11 percent in the worst case (lower bound and $T_b = 100$ ms) to 61 percent in the best case (upper bound and $T_b = 10$ ms). If half of the H-ONUs are configured as CH-ONUs, the maximum and minimum energy savings are 31 and 6 percent, respectively.

We've characterized the energy savings gain per ONU in a T_b when our solution is in place. However, it's important to quantify the total energy savings per OLT. Usually, an OLT manages 16, 32, 64, or 128 ONUs. An upper and lower bound will limit the total energy savings that our solution generates per OLT. The upper bound is defined by a case in which there is no downstream traffic for any ONU. The lower bound occurs when there is always data traffic for all ONUs in each T_b . In practice, if we consider a given time window, we will find a mix of cases in which there is downstream traffic

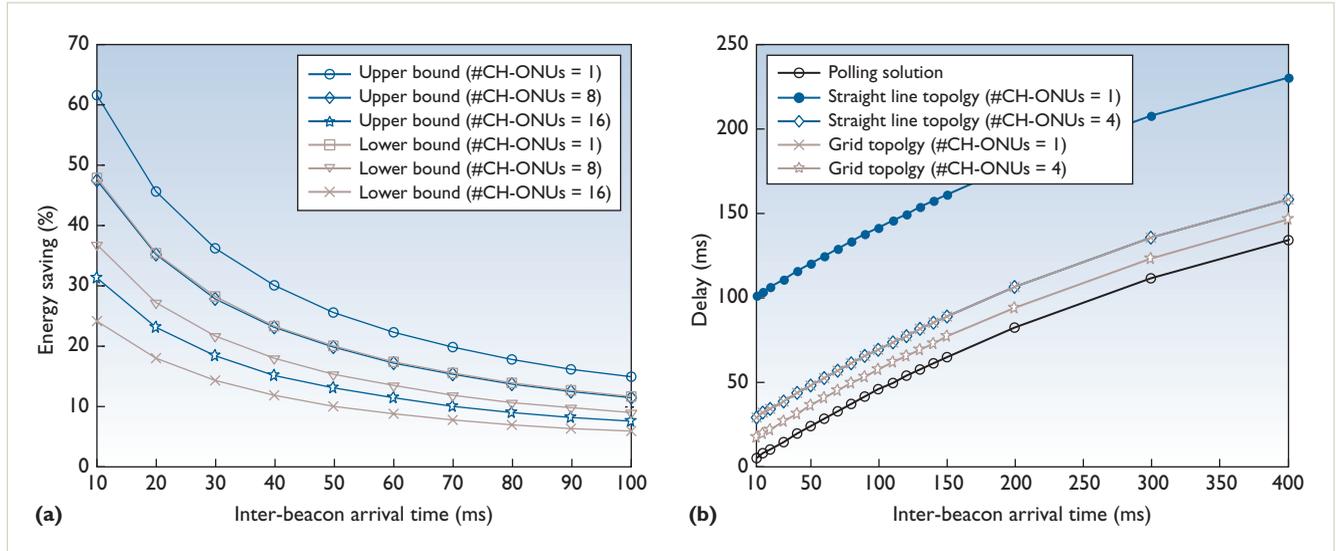


Figure 3. Results. (a) Energy saving when we use the proposed approach instead of the polling solution, assuming an optical line terminal (OLT) has 32 optical network units (ONUs) ($T_b = 10-100$ ms; CH-ONUs = 1, 8, and 16). The longer the T_b , the lower the energy savings compared to the polling solution. (b) Delay comparison between proposed and polling solution assuming an OLT has 32 ONUs ($T_b = 10-400$ ms).

available for some ONUs, and no traffic for others. Therefore, the actual energy saving will be some value between the upper and lower bounds.

Delay

To mitigate the extra delay imposed by the WSN notification network, the OLT can select more than one CH-ONU or reduce the T_b length (we explain this concept in the next section). Selecting more than one CH-ONU leads to splitting the WSN into several smaller clusters, thus reducing the number of hops to reach all H-ONUs (see Figure 4).

We followed the mathematical model presented by Danping Ren and his colleagues⁸ to calculate the average delay experienced by downstream frames depending on the selected T_b . We found that the delay associated with OLT beacon notification to ONUs (polling solution) and a CH-ONU (proposed solution) is the same. However, the delay experienced in our solution by the remaining H-ONUs before receiving a WSN-NM depends on the number of hops between the CH-ONU and each H-ONU. At this point, we should clarify that the average and maximum number of hops in the WSN are related to the WSN topology. We can then find topologies in which all the H-ONUs are reachable within only one hop, whereas in some other topologies, they can be reached using several hops. We consider two different topologies: grid and straight line (see Figure 4).

Figure 3b shows the average delay for the polling solution (from OLT to ONU), and quantifies the average delay from OLT to CH-ONU plus the maximum WSN delay in our solution. Therefore, we establish the comparison in the worst possible case for us. We also evaluate different numbers of CH-ONUs under two topologies.

As expected, we get the worst result when our solution faces a straight-line topology and only one CH-ONU is in place (16 hops are required to reach the furthest H-ONU from a CH-ONU placed in the middle of a straight line). In this case, our solution generates a maximum of 96 ms of extra delay over the polling solution. The delay is drastically reduced in a more friendly scenario such as a grid topology. In particular, when we use a single CH-ONU, the maximum extra delay is only 24 ms. Finally, we can perceive in the graph that when the number of CH-ONUs grows to four in the straight-line topology, the delay difference between two solutions is reduced by four. Using the same increment in the number of CH-ONUs reduces the extra delay to 12 ms in the grid topology.

Energy Savings Meeting PON Delay Requirements

Here, we fix a suitable T_b in the polling solution, whereas in our solution we also fix the length of T_b for different numbers of CH-ONUs, accounting for the maximum WSN delay. Later, we'll

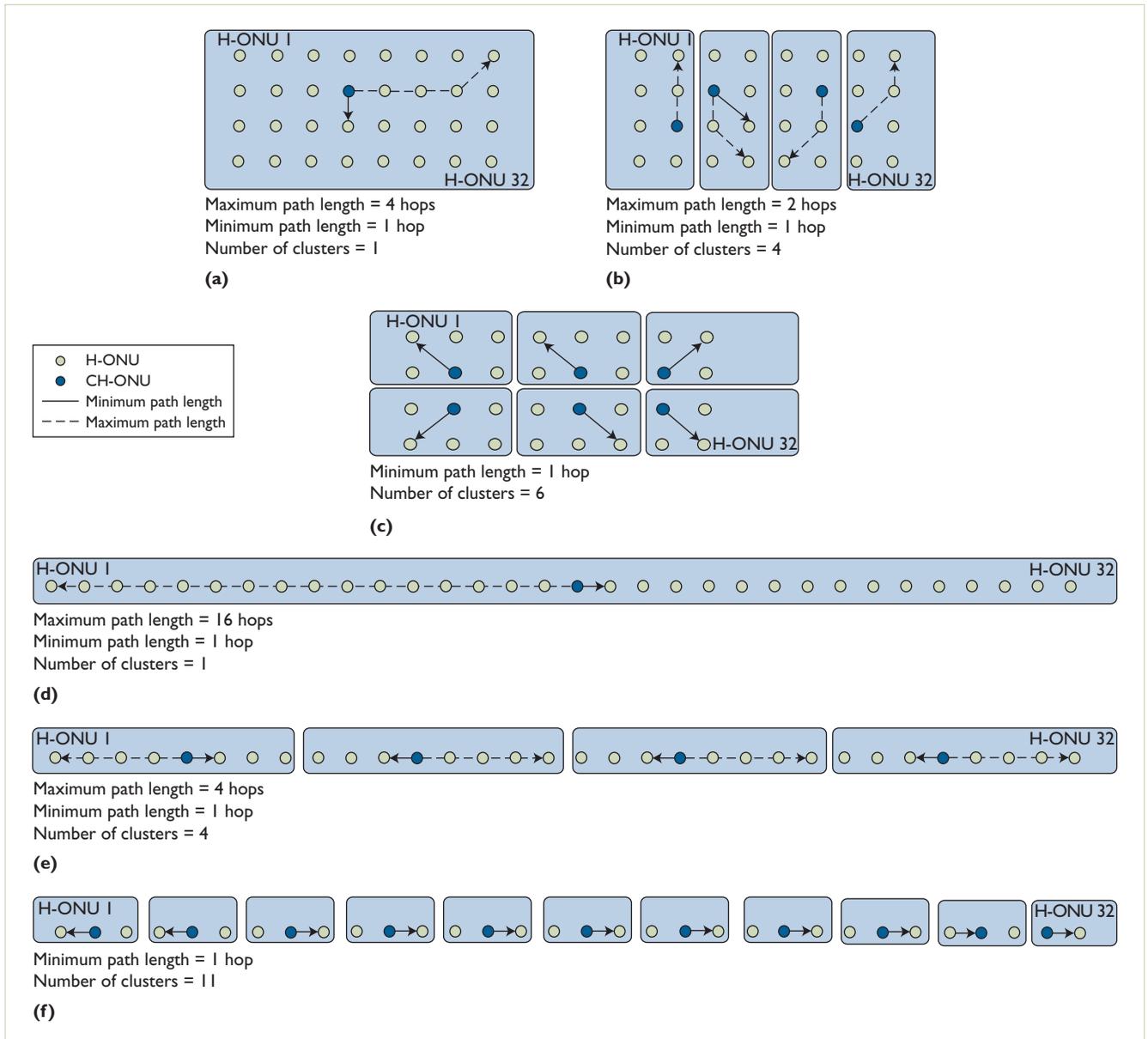


Figure 4. Examples of WSN notification network topologies formed by IEEE 802.15.4 modules of 32 hybrid optical network units (H-ONUs): (a) grid topology with one coordinator H-ONU (CH-ONU), (b) grid topology with four CH-ONUs, (c) grid topology with six CH-ONUs (six CH-ONUs are enough to reach any H-ONU within a single hop; hence, it doesn't make sense to use more than six CH-ONUs in a grid topology for this scenario), (d) straight-line topology with one CH-ONU, (e) straight-line topology with four CH-ONUs, and (f) straight-line topology with 11 CH-ONUs (11 CH-ONUs are enough to reach any H-ONU within a single hop; hence, it doesn't make sense to use more than 11 CH-ONUs for this scenario).

show the actual lower- and upper-bound of energy saving when applying our solution instead of the polling approach.

Table 1 compares the energy savings of our solution to the polling solution under the same delay restriction and two different topologies. In both topologies, increasing the number of CH-ONUs reduces the WSN delay, letting us

use longer T_b . However, after a certain number of CH-ONUs (11 for the straight topology and six for the grid in this scenario), energy gain decreases without any improvement in delay performance. This is because for that number of CH-ONUs, all of the H-ONUs are already reachable within one hop (see Figures 4c and 4f). In addition, although we select smaller T_b than in

Table 1. Energy savings of the proposed solution under different access delay requirements.

Delay requirement (ms)	T_b in polling solution (ms)	Straight topology		Percentage energy savings over the polling solution (upper bound/lower bound)	Grid topology		Percentage energy savings over the polling solution (upper bound/lower bound)
		No. of CH-ONUs	T_b in proposed solution (ms)		No. of CH-ONUs	T_b in proposed solution (ms)	
100	260	1	10	-1.84/-4.83	1	183	6.15/4.16
		2	120	5.45/2.42	4	220	5.5/3.9
		4	183	5.25/3.42	6	238	5.13/3.84
		5	200	5.1/3.54	8	238	4.6/3.4
		7	222	4.7/3.45			
		11	240	4/2.9			
		16	240	2.9/2.1			
50	112	2	NP		1	55	12.66/6.6
		4	55	10/4.5	4	82.56	11.5/7.7
		5	68.5	10.6/5.82	6	97	10.8/7.8
		7	82.6	9.55/6.3	8	97	9.72/7.06
		11	97	8.2/5.8			
		16	97	5.65/3.87			
25	53	2	NP		1	NP	
		4	NP		4	27	18.5/8.85
		5	14.2	8.85/0	6	40	18.7/12.7
		7	26.7	13.6/4.9	8	40	16.6/11
		11	40	13.4/8.5			
		16	40	8/4.3			
15	31	2	NP		1	NP	
		4	NP		4	NP	
		5	NP		6	18.33	24.2/13
		7	NP		8	18.33	20.26/9.98
		11	18.3	14.3/5.3			
		16	18.3	4/0			

Notes: The TDM passive optical network we consider has 32 optical network units (ONUs). NP = not possible; that is, the number of CH-ONUs isn't sufficient to satisfy the PON delay requirement in the proposed solution.

the polling solution, we still can save energy because just a few H-ONUs (those selected as CH-ONUs) are affected by the length of T_b , whereas in the polling solution, all 32 ONUs spend more energy if T_b is reduced.

For example, assume the PON delay requirement is 100 ms and the H-ONUs in our network form a straight topology. If the OLT selects four CH-ONUs, the delay requirement is satisfied when $T_b = 183$ ms in our solution, as Figure 3b shows. Then, based on the T_b value (that is, 183 ms), we calculate the percentage of energy savings (that is, 5.25 percent for the upper bound and 3.42 percent for the lower bound) over the polling solution.

Using the same procedure, we get the results for the different delay requirements in Table 1.

For all the evaluated delay requirements, our proposal improves upon the polling solution in terms of energy expenditure. The energy gain goes from low values (such as 2 percent) when the operator has low requirements in terms of delay (such as 100 ms) to almost 25 percent (upper bound) under strict delay requirements (such as 15 ms). Additionally, by looking at the results in the table, it's easy to define the optimal number of CH-ONUs in terms of energy saving to satisfy the imposed delay requirements. Therefore, the proposed solution significantly reduces

the energy consumption in a TDM-PON compared to the polling approach while satisfying the PON delay requirements.

To reduce energy consumption in TDM-PONs, researchers from industry and academia have been focusing on both MAC and physical layers of ONUs. In the MAC layer, efficient sleep mode management is increasingly important to maximize energy saving in ONUs, while satisfying the QoS of different applications. So, many research efforts focus on this issue. In the physical layer, developing optical transceivers and circuitry with low-power consumption and low-response time has become an important research area for maximizing energy saving in PONs. In addition, some proposals suggest that an ONU needs the ability to turn off its components deliberately whenever they have no role to perform. This approach would undeniably improve energy saving in an ONU.

Here, we've demonstrated that existing sleep mode based solutions proposing an active polling to receive downstream traffic are incurring an extra energy expenditure in ONUs. Rather, it would be interesting to find solutions in which ONUs only enter into active mode in case some downstream traffic is available for them. To make an ONU active only when they have some traffic to receive, we can rely on another low-cost low-power technology which overtakes the role of notifying ONUs when some traffic is available for them in the OLT. □

Acknowledgments

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