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Energy Efficient and Delay Optimized TDMA Scheduling for Clustered Wireless Sensor Networks

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***Abstract* — This paper studies time division multiple access (TDMA) scheduling with both energy efficiency and optimized delay in clustered wireless sensor networks (WSNs). To achieve this goal, we first build a cross-layer optimization model for attaining network wide efficient energy consumption. We solve this model by transforming it into simpler sub-problems that can be solved using conventional methods. We then propose a TDMA scheduling algorithm based on the input derived from the cross-layer optimization model. The proposed algorithm utilizes the slot reuse concept, which significantly reduces the end-to-end latency in WSNs, while retaining the feature of energy efficiency. In addition, the proposed solution in this paper is applied to clustered WSNs. This feature facilitates the application of our approach in large size WSNs.**

I. INTRODUCTION

In static wireless sensor networks (WSNs), time division multiple access (TDMA) scheduling is said to be more effective than contention based protocols such as carrier sensing multiple access (CSMA), especially when the traffic load is significant [1]. However, existing TDMA scheduling approaches in WSNs mainly focus on obtaining shortest schedules [2] [3] or distributed implementation [2] [4]-[6] without considering energy efficiency, which is in fact a key concern of WSNs.

In some recent works the researchers start considering energy efficiency in designing TDMA schedules. For example, in [7] the authors derive interference free TDMA schedules based on a nonlinear cross-layer optimization model, with the objective of achieving longest network lifetime (i.e., before the first node runs out of its energy). However, this approach uses one single frame for all nodes in a WSN, which causes significant delay as the network size increases. A similar work is done in [8], in which slot reuse is adopted to reduce the end-to-end latency. However, in order to derive the schedule, the authors propose an algorithm that iteratively solves a non-linear optimization model. This approach results in significant complexity of the scheduling algorithm, thus the algorithm only applies to very small size WSNs as well.

Our proposed TDMA scheduling algorithm in this paper is based on a nonlinear cross-layer optimization model aimed at achieving efficient network wide energy consumption. It is distinctive from previous works in three aspects. First, we transform the nonlinear optimization problem into simpler sub-problems that can be solved using conventional methods. This reduces the complexity compared to solving the original nonlinear problem. Secondly, slot reuse is adopted when the interference caused are negligible. This reduces end-to-end latency while at the same time avoids energy waste on extra retransmissions caused by the interference. Finally, the proposed solution is applied to clustered WSNs, such that only cluster heads (CHs) and gateways (if present) are considered in the optimization model and scheduling algorithm. This feature enables the application of our solution in large size WSNs..

The rest of the paper is organized as follows: Section II presents the cross-layer optimization model. In Section III we propose the scheduling algorithm. Numerical results are shown in Section IV, and we conclude the paper in Section V.

II. SYSTEM MODEL

The cross-layer optimization model is built upon the following assumptions on the wireless sensor network model, and the physical, medium access control (MAC), and network layers of a single sensor node:

1) ***Network model***: The network is divided into multiple clusters, each composed of a CH, one or several gateways (if adopted by the specific clustering scheme), and cluster members, as shown in Fig. 1. In this paper we use the clustering scheme presented in [9], but our proposed solution can also be applied to other clustering schemes. There is no limit to inter-cluster communications among CHs and gateways towards the only sink in the network, which is shown in Fig. 1.a. However, intra-cluster communication between a cluster member and its corresponding CH is limited to one hop (i.e., direct communication between a cluster member and its CH), as is the case in most clustering schemes. To simplify the analysis, we use a "virtual" link, as shown in Fig. 1.b, representing the traffic from all cluster members in a cluster to the corresponding CH. In this way, we can focus on the backbone network (composed of CHs and gateways) when deriving the TDMA schedules without looking into the details of each cluster.

We assume the network topology (such as the position of each node) is known from network deployment phase or by global positioning system (GPS) devices. The network operation is divided into rounds. Each round is composed of an initialization phase and a data relay phase. The former takes much less time than the latter thus its energy consumption can be neglected. During the initialization phase, a contention based protocol is used to form clusters, and relay necessary information such as the CHs, gateways, and data generation rate at each CH to the sink, for composing and calculating the cross-layer optimization model. Then, in the data relay phase data is transferred according to the schedule derived from the scheduling algorithm. In this paper, we will not go into details of these operations but focus only on the optimization model and scheduling algorithm.

We use a graph $G = (V, L)$ to denote the backbone network, where V and L are the sets of nodes and links, respectively. The network has $N = |V|$ nodes, in which the sink is node #1. Links are assumed to be directional in the network.

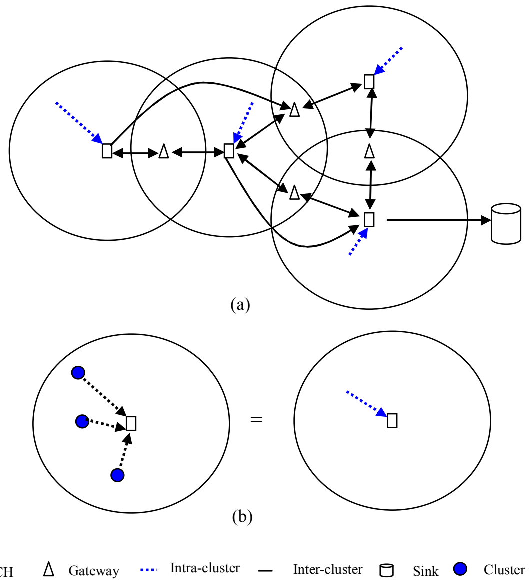


Fig. 1 Network model

2) ***Physical layer*:** We assume the average path loss, *Pl(.)*, is [10]:

$$Pl(d) = Pl(d_0) + 10n\log_{10}(d/d_0) \quad (1)$$

where d is the distance between the transmitter and receiver, d_0 is the reference distance, and n is the path loss exponent. Suppose Mica2 motes [11] are used which adopt noncoherent FSK modulation, the bit error rate, P_e, can then be expressed as [12]:

$$P_e = \frac{1}{2} e^{\frac{-SINR}{2}\frac{B_N}{R}} \quad (2)$$

where R is the data rate in *bps* (bits per second), B_N is the noise bandwidth, and *SINR* is signal to interference plus noise ratio. If the interference is small enough, for example, less than *10%* of the noise, the interference can then be neglected and we can use signal to noise ratio *(SNR)* instead of *SINR*. The *SNR* at a receiver at distance d from the sender is:

$$SNR(d)_{dB} = P_{tx\ dBm} - \overline{Pl(d)}_{dB} - P_{n\ dBm} \quad (3)$$

where P_{tx} and P_n are the transmission power and thermal noise power, respectively.

Suppose the frame length of a packet is F bytes, the encoding rate is ρ, then the packet loss rate, p, defined as the probability that at least one bit in the packet is corrupted, can be written as:

$$p = 1 - (1 - P_e)^{8\rho F} \quad (4)$$

We now consider the energy consumption model. Since energy consumption by the CPU is usually negligible, and the energy consumed by sensing tasks is environment determined, we can focus on the radio energy consumption, which is adjustable and determines the optimal energy consumption scheme. We assume the per bit transmission energy consumption at transmit power P_{tx} is:

$$E(P_{tx}) = \frac{1}{R}(P_{cir} + P_{tx}) \quad (5)$$

where P_{cir} is the fixed circuit power. P_{tx} is adjustable with the transmission range and packet loss rate requests. Per bit average receiving energy consumption at receive power P_{rx} is assumed to be fixed, and given by $E(P_{rx}) = \frac{1}{R} P_{rx}$.

3) ***MAC layer*:** TDMA schedule is derived for data relay. We assume retransmissions are supported using NACK feedbacks. With packet loss rate *p*, the average transmission tries for a packet is $1/(1-p)$. To simplify the analysis, we neglect the effect of NACKs by using a fixed period for feedbacks. That is, NACK is only generated periodically to inform the sender of packets lost in the last period. The energy consumed by NACKs can be neglected if the period is properly set.

4) ***Network layer*:** Each backbone node is allowed to have multiple input and output flows. The sink provides every backbone node with the information of its multiple next hops after deriving the optimal schedules.

Now, based on all the above assumptions, we build the following optimization model:

$$\text{min.} \quad \begin{aligned}&\Big(\sum_{i=2}^{N}\sum_{j=1}^{N} E(P_{tx,ij})\frac{1}{1-p_{ij}} f_{ij} + \sum_{i=2}^{N}\sum_{j=2}^{N} E(P_{rx})\frac{1}{1-p_{ij}} f_{ij} \\ &+ \sum_{i=2}^{N} \lambda_i E(P_{rx})\Big), \ (i,j) \in L, i \neq j\end{aligned} \quad (6a)$$

$$\text{s.t.} \quad f_{ij} \geq 0, \ i \in [2, N], j \in [1, N], i \neq j \quad (6b)$$

$$f_{ij} = 0 \ \ iff \ \ (i,j) \notin L \ or \ i = j \quad (6c)$$

$$\sum_{j=1, j\neq i}^{N} (f_{ij} - f_{ji}) = \lambda_i / C_i, \ i \in [2, N] \quad (6d)$$

$$\sum_{i=2}^{N}\sum_{j=1}^{N} \frac{1}{1-p_{ij}} f_{ij} \leq R, \ i \neq j \quad (6e)$$

$$\begin{aligned}&\sum_{j=1, j\neq i}^{N} \Big(E(P_{tx,ij}) f_{ij} \frac{1}{1-p_{ij}} + E(P_{rx}) f_{ji} \frac{1}{1-p_{ji}}\Big) \\ &+ \lambda_i E(P_{rx}) \leq e_i \ \ i \in [2, N]\end{aligned} \quad (6f)$$

where $P_{tx,ij}$ is the transmission power from node i to j, $E(P_{tx,ij})$ is the average per bit transmission energy consumed at node i when transmitting to node j using transmission power $P_{tx,ij}$, p_{ij} is the packet loss rate on link *(i, j)*, f_{ij} is the data flow rate (in *bps*) from node i to j without considering the retransmissions, λ_i is the new generated traffic (in *bps*) and C_i is the traffic compression rate at node i if node i is a source

CH, R is the maximal network bandwidth or largest allowed link data rate (in *bps*), and e_i is the allowed maximum consumed energy per unit time at node i (e.g., $e_i = e_{i,avail} / T$, where $e_{i,avail}$ is the initial available energy in *mJ* at node i and T is a fixed lifetime in seconds).

The objective function in (6a) gives the total consumed energy of the whole backbone network per unit time (i.e., *mJ/sec=mW*), which is composed of transmission energy consumption and receiving mode energy consumption at every backbone node, excluding the sink. The energy consumed at the sink is neglected because its power source is replaceable.

The first two constraints (6b) and (6c) state that the flow rate should be non-negative and flows can only exist on valid links. The third constraint (6d) indicates that the output data rate at each node should be the sum of input data rate and data generation rate (the data is generated by cluster member nodes, compressed at the corresponding CH and then relayed to the sink) at that node. The fourth constraint (6e) is the data rate or bandwidth limit of the network, showing that the summed data rate with retransmissions at all links should not be greater than the maximal allowed data rate. In a WSN adopting slot reuse approach, this is a conservative constraint. The fifth constraint (6f) is the per unit time energy consumption constraint at every node.

Applying (1)-(5), the model in (6) is non-linear. To solve (6), we first solve (7) to calculate the optimal transmission power on each link (*i, j*), $P_{opt,tx,ij}$, which achieves least energy consumption, $E_{opt,ij,txrx}$, for relaying (transmit from node *i* and receive at node *j*) one bit on the link.

$$\text{min. } (E(P_{tx,ij}) + E(P_{rx,ij}))\frac{1}{1-p_{ij}} \quad (i,j) \in L$$

$$\text{s.t.} \quad lb < P_{tx,ij} < ub \quad i \in [2,N], j \in [1,N] \qquad (7)$$

where *lb* and *ub* are the lower and upper bounds of the transmission power, respectively. The golden section search method [13] can be used to solve (7).

We now make the following statement:

Lemma 1: For the optimal energy consumption model proposed in (6), on any link (*i, j*), the model must use the optimal transmission power of this link, $P_{opt,tx,ij}$, to achieve network-wide optimal energy consumption.

Proof: Assume the optimal network-wide per bit relay energy consumption is $E_{opt,total} = X + E_{ij,txrx}$, where $E_{ij,txrx}$ is the per bit relay energy consumption on link (*i, j*), and X is the per bit relay energy consumed by the other links in the network. Suppose the transmission power at link (*i, j*), $P_{tx,ij}$, is different from $P_{opt,tx,ij}$, the optimal transmission power of this link, we then have $E_{ij,txrx} > E_{opt,ij,txrx}$. Thus, $(E_{opt,total} = X + E_{ij,txrx}) > (E'_{opt,total} = X + E_{opt,ij,txrx})$, which contradicts with the statement that $E_{opt,total}$ is the optimal network wide per bit relay energy consumption.

According to Lemma 1, we can input parameters $P_{opt,tx,ij}$ and corresponding p_{ij} from solving (7) into (6), thus get the optimal solution of (6). This transforms the non-linear optimization problem into a linear minimum network flow problem [14], and can be solved accordingly.

III. MINIMUM DELAY TDMA SCHEDULING

Using per link transmission power and flow distribution derived from (6) as the input, we now propose the TDMA scheduling algorithm. The scheduling includes both inter-cluster and intra-cluster scheduling. The former is responsible for assigning slots to all backbone links and virtual links, and the latter assigns the virtual link slots to links between cluster members and the CH in each cluster. Intra-cluster slot assignment is usually done by the CH (e.g., [15]) and is straightforward, thus we focus on the inter-cluster scheduling only.

We define a frame of length M (*>1*) composed of M fixed-length time slots. Let the slot length be Δt (*<1 sec.*). For a link *(i, j)* with flow f_{ij}, maximum data rate R (both in *bps*), and per-hop packet loss rate p_{ij}, the slots needed per second are:

$$M_{ij} = \left\lceil \frac{f_{ij}}{R\Delta t(1-p_{ij})} \right\rceil, i \in [2,N], j \in [1,N] \qquad (8)$$

where $\lceil x \rceil$ is the smallest integer greater than or equal to x. Decreasing the slot length Δt can reduce the error introduced by the ceiling function in (8).

Assume the number of slots needed by the virtual link of CH *i* is $M_{v,i}$, the slots needed per second at a backbone node *i* (CH or gateway) are thus given by:

$$M_i = \begin{cases} M_{v,i} + \sum_{j=1}^{N} M_{ij}, \ i \in CHs \\ \sum_{j=1}^{N} M_{ij}, \ i \in Gateways \end{cases} \quad i \in [2,N], \ i \neq j \qquad (9)$$

To reuse a slot *s* on one of node *i*'s links, as shown in Fig. 2, the following reuse criteria must be simultaneously satisfied:

Criterion 1: Node i is not the sender or receiver of a previously scheduled link using slot s, and the link of node i to be scheduled with slot s does not have the same receiver as that of previously scheduled link using slot s.

Criterion 2: *scheduling s as a slot used by one of node i's links causes negligible interference to the receiver of a previously scheduled link also using slot s;*

Criterion 3: *The sender of a scheduled link using slot s causes negligible interference to current receiver if using slot s on one of node i's links.*

In this paper, we assume that the interference at a node is negligible only if it is less than *10%* of the noise floor.

Finding the shortest TDMA schedule in WSNs is proved to be NP-hard [2]. In our case, the transmission power and flow distribution on each backbone link or virtual link is not uniform, which further complicates the problem. We therefore propose the following scheduling algorithm for inter-cluster scheduling:

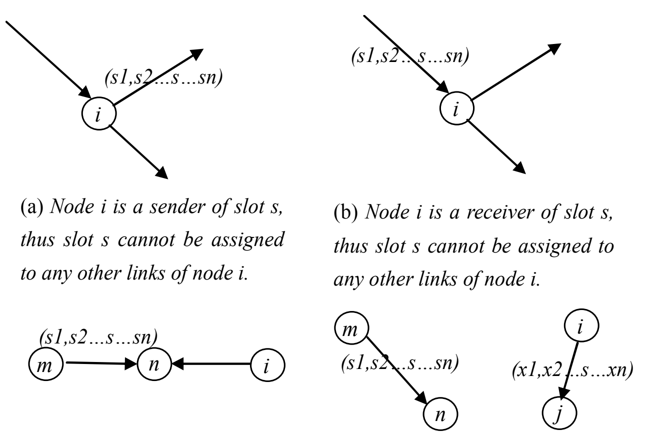
Algorithm 1 – Finding a conflict free schedule

Input: The backbone network: $G=(V, L)$, number of nodes in the backbone network: $N=|V|$, slots needed at node i: M_i, the distance between nodes i and j: D_{ij}, and the transmission power on link (i, j): $P_{tx,ij}$.

Output: A conflict free schedule with frame length M.

```
Begin
    for i=2 to N do /*#1 is the sink*/
    /*Determine the slots (i.e., slot IDs) being used
    by all outgoing links and the virtual link (if
    present) of node i*/
        for m=1 to M_i do
            s=1;
            /*Check conflicts and interference with all
            previously scheduled links also using slot s,
            until a feasible slot is found.*/
            while (Criterion1 or Criterion 2 or Criterion
            3 is not satisfied)
                s=s+1;
            Schedule s as a slot of one of node i's links;
        end for
    end for
end
```

The maximum slot ID derived from Algorithm 1 is M. Since M_i is defined as slots needed *per second* at any backbone node i, $M\Delta t$ should be less than 1. Otherwise, we need to decrease Δt and run the algorithm again until $M\Delta t \le 1$. The complexity of Algorithm 1 is $O(N^2)$.



(a) *Node i is a sender of slot s, thus slot s cannot be assigned to any other links of node i.*

(b) *Node i is a receiver of slot s, thus slot s cannot be assigned to any other links of node i.*

(c) *Slot s is assigned to link (m, n), thus cannot be assigned to link (i, n) .*

(d) *Transmission from node m to n causes negligible interference to j; and transmission from node i to j causes negligible interference to n.*

Fig. 2 (a)(b)(c): Criterion 1; (d): Criteria 2 and 3

IV. NUMERICAL RESULTS

We configure the parameter values assuming the Mica2 motes [11], and set R = 19.2 kbps, B_N = 30 kHz, ρ = 2 (Manchester encoding), F = 50 bytes, P_{cir} = 15 mW, and P_{rx} = 22.2 mW. For the path loss model, we set d_0 = 1 m, $Pl(d_0)$ = 55 dB, n = 4, and P_n = −105 dBm [16]. Without loss of generality, we set $C_i = 1$.

In the first experiment, we investigate how the optimal transmission behavior is affected by the transmission, circuit, and receiving mode power, and compare the energy efficiency of the proposed cross-layer model to two other relay schemes:

1) Hop by hop: Data at a backbone node is relayed one hop (specified by a hop distance) towards the sink each time, using optimal transmission power for each relay.

2) One hop: Data at a backbone node is transmitted directly to the sink, using optimal transmission power on the direct link.

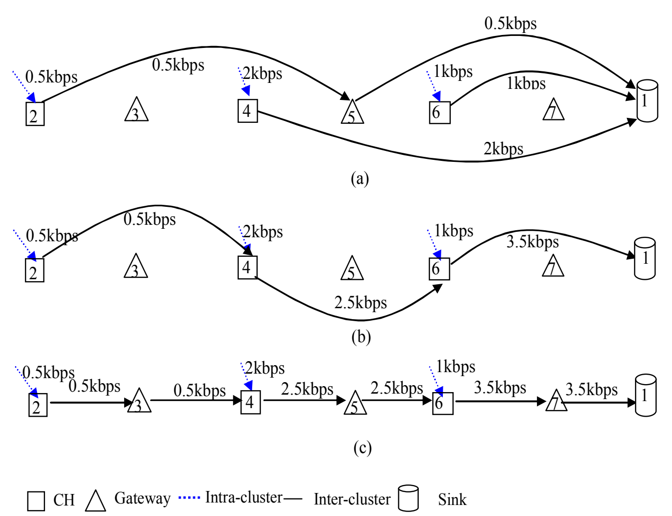


Fig. 3 Optimal relay schemes for: (a) Hop distance = 5m; (b) Hop distance = 10m; (c) Hop distance = 15m

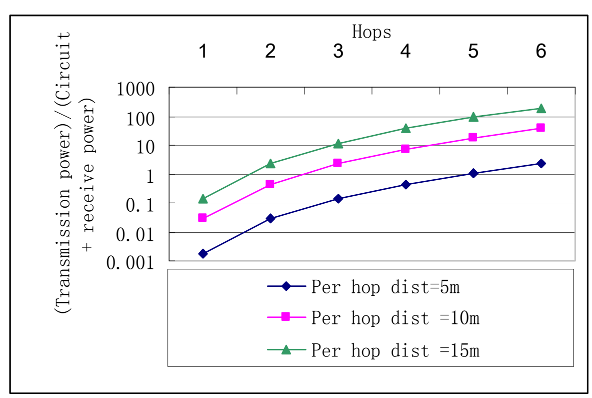


Fig. 4 (Transmission power)/(circuit + receiving mode power)

We use a linear backbone network as shown in Fig. 3. The hop distance in Figs. 3.a, 3.b and 3.c are set to *5*, *10*, and *15* meters, respectively. The operation period is set to one day and the residual energy at each node is *6000J*. The data generation rate at CHs *2*, *4* and *6* are 0.*5, 2*, and *1 kbps*, respectively. Referring to Fig. 4, we realize that the transmission behavior is mainly determined by the ratio of *transmission power/(circuit + receiving power)*. If the fixed circuit and receiving mode power is dominant, as shown in Figs. 3.a and 3.b, data is relayed with less intermediate nodes to reduce circuit and receiving mode power consumption at intermediate nodes. On the contrary, if the transmission power is dominant, it is seen from Fig. 3.c that data is relayed in hop by hop manner to avoid significant transmission power consumption with larger transmission range.

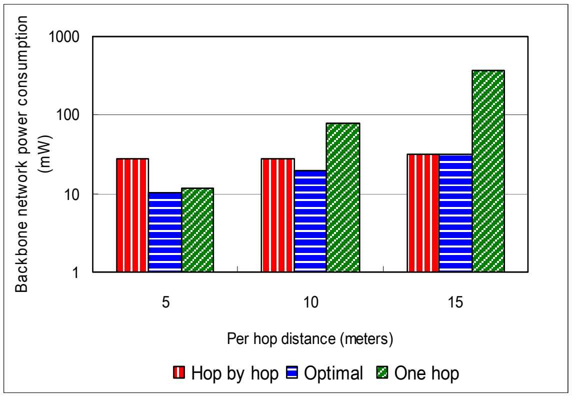


Fig. 5 Power consumption under different relay schemes

Fig. 5 gives the power consumption under different relay schemes. Combined with Fig. 4, it is seen that hop by hop relay, which is usually used in WSNs and mobile ad hoc networks (MANETs), is power efficient only if hop by hop transmission power is dominant compared to the circuit and receiving mode power. On the contrary, one hop direct relay is only preferred if the circuit and receiving mode power is dominant. So, relay scheme selection without considering the values of transmission, circuit, and receiving mode power may lead to energy inefficiency in WSNs.

In the second experiment, we use the *15*-meter hop distance scenario as shown in Fig. 3.c. All configurations are the same except that the residual energy at node 4 is now set to 500*J*. In Fig. 6.a, it is seen that part of the traffic from node 3 has to be transmitted by a suboptimal path (i.e., 3 to 5 instead of 3 to 5 via 4), due to the residual energy constraint at node 4. We then conclude that a WSN with redundant nodes may reduce the chance of suboptimal paths selection and achieve better transmission efficiency (e.g., a redundant backup node of node 4 in this experiment can avoid the path from 3 to 5, when node 4 runs out of energy).

By setting per time slot length, Δt, to *10* milliseconds and applying (9) to every link in Fig. 6.a, including the virtual links, we have the number of slots needed as shown in Fig. 6.b. Running Algorithm 1 gives the slot assignment solution presented in Fig. 6.c. The final output is a frame of *94* slots with duration of *940* milliseconds. By reducing Δt to *5* milliseconds, we can reduce the error caused by Δt in (8) and have a frame of *915* milliseconds. Slots are reused from node 6. Obviously, as the network size increases, more and more slots can be reused and our proposed Algorithm 1 is especially beneficial for large size WSNs in reducing latency.

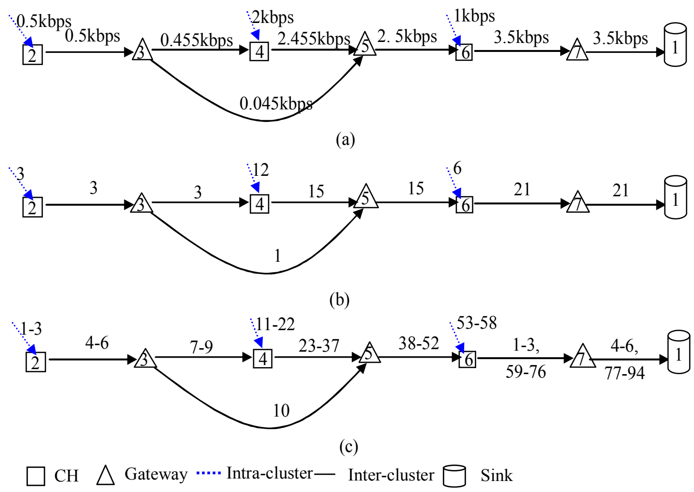


Fig. 6 (a) The effect of per node residual energy constraints; (b) Number of slots needed on each link; (c) Assigned slots and slot reuse

Finally, we consider a matrix similar backbone network in the third experiment to evaluate the proposed solution in this paper. In Fig. 7, the distance between neighboring backbone nodes in the same row or column is *10* meters, and the radius of each cluster is *15* meters. We set the data generation rate at each CH to *0.2 kbps*, the residual energy at each backbone node to *6000J* and the operation time to one day. The relay scheme presented in Fig. 7.a further proves one of the conclusions drawn in the first experiment. That is, widely adopted hop by hop relay in WSNs and MANETs may not be energy efficient. In Fig. 7.b we also show a schedule derived by running Algorithm 1 for this scenario. With Δt set to *10* milliseconds we have a frame of *98* slots, of which *14* slots are reused even in this small size network.

V. CONCLUSION

We build a cross-layer optimization model that achieves efficient network wide energy consumption. By transforming the problem into simpler sub-problems, we solve the problem using conventional methods such as golden section search and minimum network flow linear programming. Using the results derived from the optimization model as input, we further propose a TDMA scheduling algorithm that can work in WSNs with non-uniformly distributed traffic loads and varied transmission power on the links. This algorithm utilizes the slot reuse concept to significantly reduce the latency. Simulation results from both linear and matrix similar backbone networks reveal the power efficiency and delay optimal features achieved by the proposed scheduling algorithm.

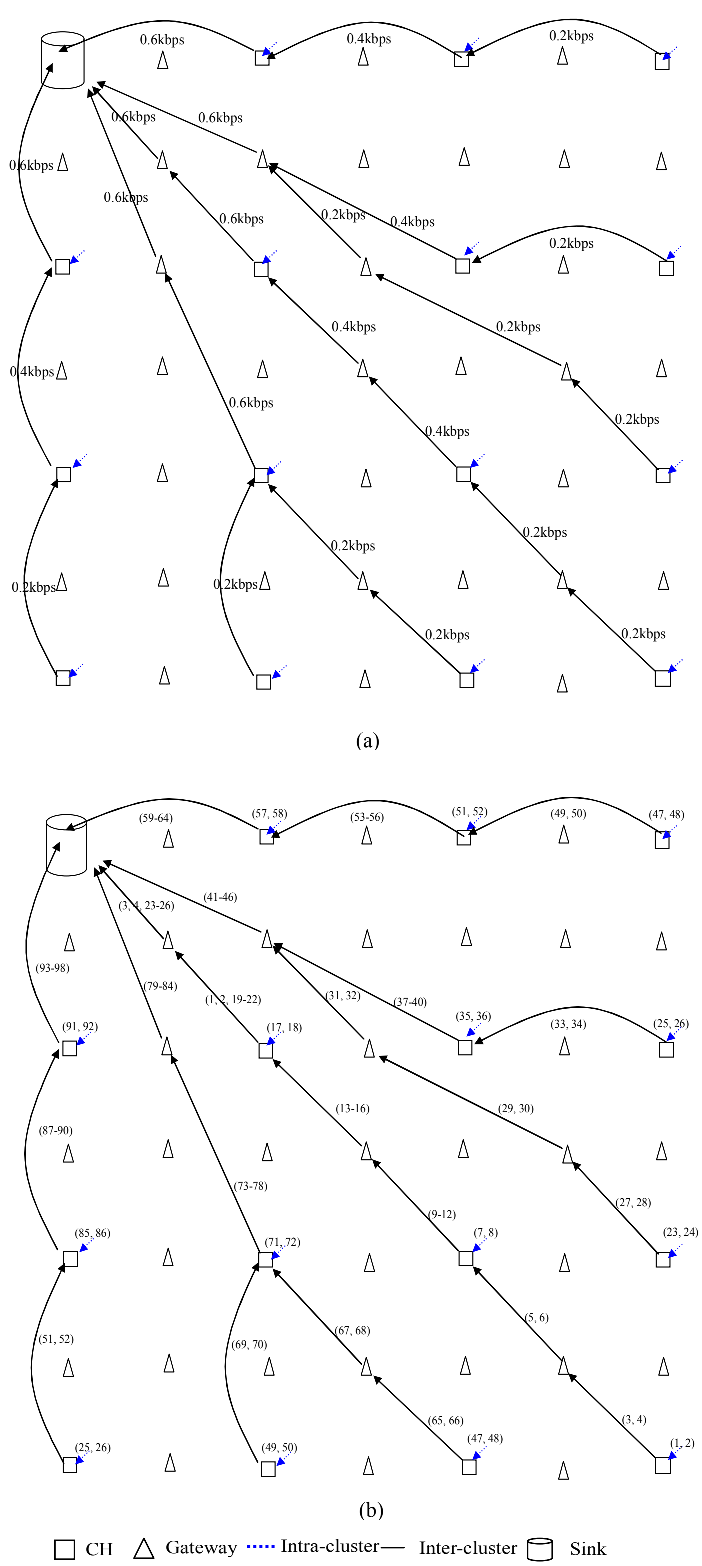


Fig. 7 (a) Relay scheme and, (b) scheduling in a more complex topology

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