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Trade-off between Energy and Delay Based on a Multi-objective Optimization Problem for Wireless Sensor Network

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Abstract: The advances of sensor technology and wireless communications have enabled the manufacturing of low priced, large-scale wireless sensor networks. The design of energy efficiency data forwarding protocols for WSN (wireless sensor network) is an essential component and critical determinant of the performance of WSN. However, prolonging the lifetime of WSN becomes challenging problems for sensing applications which are strict contraints on delay. It's clearly shown that the three goals, namely minimum energy consumption, minimum delay, and uniform energy depletion, are conflicting goals. This can be explained by the following three interpretations. First, the minimum energy consumption requires transmitting the data over short distances. Second, the minimum delay requires minimizing the number of intermediate forwarders between a source and the sink. Third, if the search space of candidate forwarders is a small area, the energy depletion of sensors will be unbalanced. In contrast, if the search space of candidate forwarders is a large area, the sensors will uniformly achieve energy depletion. Habib M. Ammari proposed a data forwarding protocol to get a balance between energy and delay, called TED (trade off energy with delay). In this paper, we propose a improved data forwarding protocol based on TED, called TED+. The simulation results showed that our proposed protocol is more efficient than TED on energy and delay.

Key words: WSN (wireless sensor network), trade-off, optimization, energy, delay.

1. Introduction

Data forwarding is a crucial factor for WSN. Source sensors send their sensing data through multi-hop wireless links to the sink sensor. The network lifetime belongs to the uniform energy depletion of the sensors. Indeed, battery power is the most critical resource in WSN, especially when battery recharging or replacing is impossible [1]. Thus, sensors must be applied energy-efficient data forwarding protocols to guarantee uniform energy depletion. This helps the sensor prolong the network lifetime. Ensuring the longevity of WSN becomes a challenging issue, especially for sensing applications with strict constraints on delay [2].

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Data forwarding protocol should be designed appropriately to achieve minimum energy consumption while ensuring uniform battery power depletion of the sensors and meeting the required delay constrains. Thus, leading to a multi-objective optimization problem.

Because minimum energy consumption, minimum delay, and uniform energy depletion are conflicting goals, which have to be dealt simultaneously, finding a trade-off between them is necessary. Indeed in Ref. [3], minimizing energy consumption requires transmitting the sensed data over short distances; energy (E_{tx}) spent in data transmission over a physical distance d between a pair of transmitting and receiving points, is proportional to d, i.e., $E_{tx} \propto d^{\alpha}$, with $2 \le \alpha \le 4$ being the path-loss exponent.

However, minimizing delay requires minimizing the number of intermediate forwarders between a source and the sink. This goal could be achieved by maximizing the distance between any pair of consecutive forwarders. Furthermore, the search space of candidate forwarders affects an unbalanced distribution of the data forwarding load amongst the sensors, thus causing a non-uniform depletion of their available energy. Indeed, the candidate forwarders located in a small search space would heavily suffer depletion of their energy as they will be frequently selected as forwarders. In contrast, a large search space ensures a more balanced data forwarding load amongst the sensors and hence helps achieve uniform energy depletion of the sensors.

There are many protocols to optimize energy and network latency in WSN [4]. In particular, Habib M. Ammari proposed a data forwarding protocol to get a balance between energy and delay, called TED (trade off energy with delay) using the multi-objective approach [5].

The remainder of this paper is organized as follows: Section 2 describes TED protocol and related works; Section 3 presents improvements from TED and proposes TED+ protocol; Section 4 simulates and evaluates performance between TED and TED+.

2. TED Protocol and Related Works [5]

TED is a new data forwarding protocol to balance minimum energy consumption, minimum delay and uniform energy depletion. This protocol is implemented in slicing the communication range into CCB (concentric circular bands) and using a WES (weighted scale-uniform sum) approach to solve a multi-objective optimization problem in WSN. This approach will find a balance between the three objectives.

2.1 Slicing of the Communication Range

The communication range of the sensors is modeled and analyzed into CCBs. It characterizes the uniform battery power depletion of the sensors. A slicing approach is based on an approximation of the minimum transmission distance d_{min} in data transmission

$$\boldsymbol{d_{min}} = (\boldsymbol{E_{elec}}/\boldsymbol{\varepsilon})^{1/\alpha} \qquad (1)$$

$$\varepsilon : transmitter\ applifier$$

$$\alpha: data\ size$$

E_{elec}: *electronics energy*

To achieve a better balance between minimum energy consumption, minimum delay and uniform energy depletion, Habib M. Ammari proposed to slice the communication range *CD* (s_i, *R*) of a sensor s_i with the radius R and the center s_i into $n_{ccb} = \left\lceil \frac{R}{d_{min}} \right\rceil$ CCBs, each of which is centred at s_i and has a width of d_{min}. The CCBs can be divided into three categories (Fig. 1). The inner CCBs favour minimizing energy consumption over minimizing delay and uniform energy depletion; the middle CCBs give the same degree of interest to the three performance metrics; and the outer CCBs favour minimizing delay and uniform energy depletion over minimizing energy consumption of the sensors.

From a NNS(s_i) (network neighbour set) of a sensor s_i, we define CPF (s_i, s_m, k, β) is a subset of the sensors, called CPF (candidate proxy forwarder) of s_i which belongs to the k^{th} CCB and located within a zone determined by a wedge with an angle β centred at s_i (Fig. 2). The size of CPF (s_i, s_m, k, β) depends on the values of k and β where $1 \leq k \leq n_{ccb}$ and $0 < \beta < \pi$.

2.2 Energy and Delay Model

Let λ be the spatial density (i.e., the number of the sensors per unit area and c = qd (queuing delay) + td (trasmission delay). The expected total number of CPFs, energy consumption, delay associated with the k^{th} CCB in forwarding a data packet from a source s_0 to the sink s_m along the shortest path [s_0, s_m] are computed as

$$|\boldsymbol{CPF_{exp}}(\boldsymbol{s_0}, \boldsymbol{s_m}, \boldsymbol{k}, \boldsymbol{\beta})| = \frac{\lambda\beta(2k-1)\delta(s_0,s_m)d_{min}}{2k} \qquad (2)$$

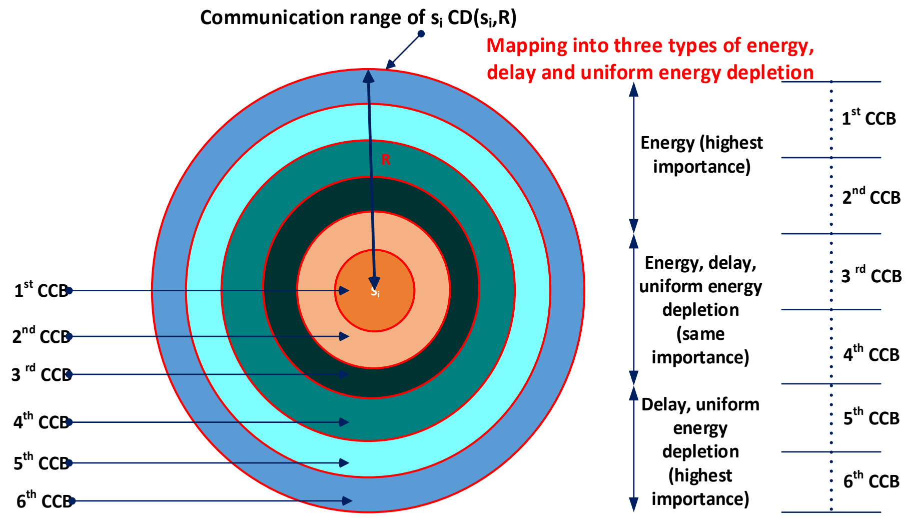


Fig. 1 **Decompose the communication range.**

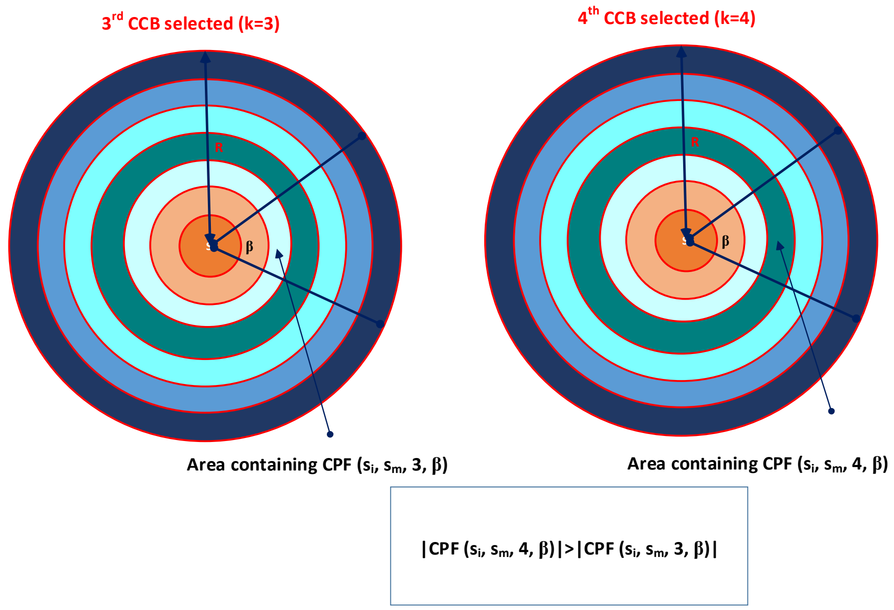


Fig. 2 **Selection of candidate proxy forwarder.**

$$\boldsymbol{E_{exp}(s_0, s_m, k) = a\left(\frac{2E_{elec}}{kd_{min}} + \varepsilon\, k^{\alpha-1} d_{min}^{\alpha-1}\right)\delta(s_0, s_m)} \quad (3)$$

$$\boldsymbol{D_{exp}(s_0, s_m, k) = \frac{c\delta(s_0,s_m)}{kd_{min}}} \quad (4)$$

In case, data forwarding along non-direct paths is the subset(s_0, s_m, k, β), the energy $E_{exp}(s_0, s_m, k)$, the delay $D_{exp}(s_0, s_m, k)$ are computed as:

$$\boldsymbol{|CPF_{exp}(s_0, s_m, k, \theta)| = \frac{\lambda\beta(2K-1)d_{min}^2\delta(s_0,s_m)}{2\psi(k,\theta)}} \quad (5)$$

$$\boldsymbol{E_{exp}(s_0, s_m, k, \theta) = \frac{b(2E_{elec}+\varepsilon k^{\alpha} d_{min}^{\alpha})\delta(s_0,s_m)}{\psi(k,\theta)}} \quad (6)$$

$$\boldsymbol{D_{exp}(s_0, s_m, k, \theta) = \frac{c\delta(s_0,s_m)}{\psi(k,\theta)}} \quad (7)$$

$$\boldsymbol{PF_{exp}(s_0, s_m, k) = -|CPF_{exp}(s_0, s_m, k)|} \quad (8)$$

where:

$\delta(s_0, s_m)$: *euclidean distance between s_0 and s_m*

$\psi(k, \theta) = kd_{min}Cos(\theta)$ (Fig. 3)

$$\theta_{max} = \frac{\beta}{2}$$

Using the WES approach, where the weights w_1, w_2, and w_3 indicate the relative importance of $E_{exp}(s_0,s_m,k)$, $D_{exp}(s_0,s_m,k)$, and $PF_{exp}(s_0,s_m,k)$, respectively, our unconstrained multi-objective optimization problem can be written as follows:

$$\textit{Minimize } M(k) \textit{ subject to } 1 \le k \le nccb$$

$$M(k) = \begin{cases} w_1 E_{exp}(s_0,s_m,k) + w_2 \dfrac{E_{exp}^{max} D_{exp}(s_0,s_m,k)}{D_{exp}^{max}} + w_3 \dfrac{E_{exp}^{max} PF_{exp}(s_0,s_m,k)}{PF_{exp}^{max}} \\ \quad \text{if } E_{exp}^{max} = \max\{E_{exp}^{max}, D_{exp}^{max}, PF_{exp}^{max}\} \\ w_1 \dfrac{D_{exp}^{max} E_{exp}(s_0,s_m,k)}{E_{exp}^{max}} + w_2 D_{exp}(s_0,s_m,k) + w_3 \dfrac{D_{exp}^{max} PF_{exp}(s_0,s_m,k)}{PF_{exp}^{max}} \\ \quad \text{if } D_{exp}^{max} = \max\{E_{exp}^{max}, D_{exp}^{max}, PF_{exp}^{max}\} \\ w_1 \dfrac{PF_{exp}^{max} E_{exp}(s_0,s_m,k)}{E_{exp}^{max}} + w_2 \dfrac{PF_{exp}^{max} D_{exp}(s_0,s_m,k)}{D_{exp}^{max}} + w_3 PF_{exp}(s_0,s_m,k) \\ \quad \text{if } PF_{exp}^{max} = \max\{E_{exp}^{max}, D_{exp}^{max}, PF_{exp}^{max}\} \end{cases}$$

$$0 \le w_1, w_2, w_3 \le 1 \text{ with } w_1 + w_2 + w_3 = 1$$

$$E_{exp}^{max} = max\{E_{exp}(s_0,s_m,k): 1 \le k \le n_{ccb}\}$$
$$D_{exp}^{max} = max\{D_{exp}(s_0,s_m,k): 1 \le k \le n_{ccb}\}$$
$$PF_{exp}^{max} = max\{PF_{exp}(s_0,s_m,k): 1 \le k \le n_{ccb}\}$$

Optimum solution of the muti-objective problem stated above:

$$k = k_1^* = k_2^* = k_3^* = \sqrt[\alpha]{\frac{2E_{elec}}{(\alpha-1)\varepsilon d_{min}^{\alpha}} + \frac{w_2 c E_{exp}^{max}}{w_1(\alpha-1)\alpha\varepsilon d_{min}^{\alpha} D_{exp}^{max}} + \frac{w_3 \pi\lambda E_{exp}^{max}}{6(\alpha-1)w_1\alpha\varepsilon d_{min}^{\alpha-2} PF_{exp}^{max}}}$$

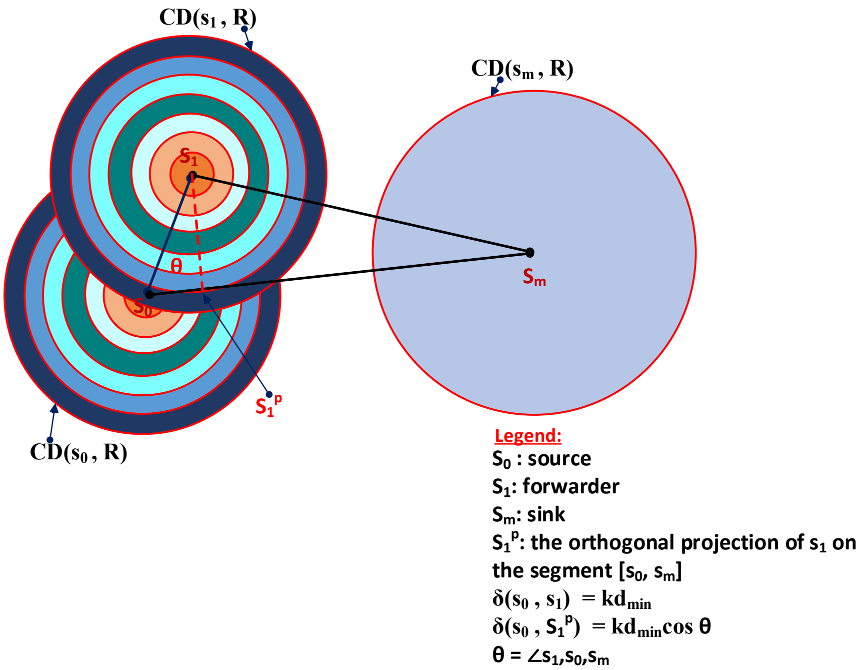


Fig. 3 Selection of proxy forwarder.

2.3 TED Protocol

TED includes three phases:

Phase 1: Decompose the communication range into n_{ccb} CCBs
Phase 2: Select an appropriate CCB using k
Phase 3: Select a proxy forwarder from k^{th} CCB
Pseudo code of TED protocol:
Begin
// Actions executed by a source s_0
Pha 1: Slice the communication range CD(s_0, R) of s_0
1. Slice CD(s_0, R) into n_{ccb} CCB
Pha 2: Select an appropriate CCB using k
2. Select the appropriate weights $0 \leq w_1$, w_2, $w_3 \leq 1$ such that $w_1 + w_2 + w_3 = 1$ to solve the multi-objective optimization problem: Minimize M(k) ($0 \leq k \leq n_{ccb}$)
3. Choose a CCB id, k, which is a solution to M(k)
4. If sink $s_m \in$ NNS(s_0) and $s_m \in k'^{th}$ with $k' \leq k$ Then
Begin
5. Or ward the sensed data directly to the sink s_m
6. Break;
End
7.Else
Begin
Pha 3: Select a proxy forwarder from k^{th} CCB
8. Identify a subset candidate proxy forwarders CPF (s_0, s_m, k) from k^{th} CCB
9. If CPF (s_0, s_m, k) = Ø Then
Begin
Randomly pick the closest q^{th} non-empty lower/higher CCB
10. k = q;
End
11. Determine the first proxy forwarder s_{PF1} such that E_{rem} (s_{PF1}) = max{$E_{rem}(s_j)$: $s_j \in$ CPF(s_0, s_m, k, $\boldsymbol{\theta}$)}
12. Forward the sensed data packet to s_{PF1}
// Actions executed by any proxy forwarder
13. While (sensed data has not reached s_m) Do
Begin
14. If sink $s_m \in$ NNS(s_{PFi}) and $s_m \in k'^{th}$ with $k' \leq k$
Then
Begin
15. Forward the sensed data directly to s_m
16. Break;
End
17. Else Replace s_0 with s_{PFi} and run steps 5-15
End
End
End

3. Improvements and TED+ Protocol

According to the WES approach it generates a unique optimization solution ($k = k_1^* = k_2^* = k_3^*$). However, the value of k depends on the weighting coefficient w_1, w_2, and w_3. TED uses the value of k generated by source s_0. This value of k is only changed as the subset CPF of k^{th} CCB is empty. In fact, the sensors are located around the sink act as relay node of all data from all sources. Thus, the sensors nearer the sink will consume more energy than others in the network. Therefore, resulting in energy consumption problem of synchronization is not really optimized for WSN.

Selecting PF (PF $\in$ CPF) based on the highest first remaining energy of the sensors in the subset CPF. This is not really optimization of energy in case CPF contain many PFs which have the same remaining energy. The PF with larger θ angle will consume more energy than the others with smaller θ angle (Eq. (6)). Moreover, the remaining energy of sensor s_i can be appropriated that $E_{rem}(s_i) = E(s_i) - (E_{rx}(s_i) + E_{tx}(s_i))$, we have $E_{tx} \propto d^{\alpha}$ (in section 1). Clearly the larger the distance between s_i and PF is, the more the remaining energy of s_i decreases.

3.1 Proposed Improvements

The first approach to improve TED protocol is to check a condition at sensor s_{m-1} before forwarding data to s_m. If $s_m \in NNS(s_{m-1})$ and $s_m \in |CPF(s_{m-1}, s_m, k'^{th} \leq n_{ccb}, \beta)|$ then forward the sensed data directly to s_m (briefly $s_m \in k'^{th}$ with $k' \leq n_{ccb}$). In fact, $|CPF(s_{m-1}, s_m, k'^{th} \leq n_{ccb}, \beta)|$ has got maximum value, i.e we have many selections of candidate proxy forwarder node at s_{m-1}. Then we uniformly ensure energy consumption of the sensors near the sink s_m. Moreover, delay will not be affected much when we choose PF in subset $|CPF(s_{m-1}, s_m, k'^{th} \leq k, \beta)|$ or $|CPF(s_{m-1}, s_m, k'^{th} \leq n_{ccb}, \beta)|$. The result is that we still obtain a better balance between energy and delay (Fig. 4).

The second approach to improve TED protocol is to choose PF with minimum θ: $\theta(s_{PF}) = \min\{\theta(s_{PFj}): s_{PFj} \in CPF(s_i, s_j, k, \boldsymbol{\theta})\}$. Energy consumption is optimal when the proxy forwarders are in the shortest path between source and sink. Thus, the total energy consumption forwarding data packet from source to sink also depends on θ angle (Fig. 5).

The third approach to improve TED protocol is to choose PF with minimum δ: $\delta(s_i, s_{PF}) = \min\{\delta(s_i, s_{PFj}): s_{PFj} \in CPF(s_i, s_j, k, \boldsymbol{\theta})\}$. The remaining energy of sensor s_i will be optimal $E_{rem}(s_i) = E(s_i) - (E_{rx}(s_i) + \min E_{tx}(s_i))$. Thus, the total energy consumption forwarding data packet from source to sink also depends on δ distance (Fig. 6).

3.2 TED+ Protocol

From the improvements to overcome the drawbacks of the TED protocol. We propose a improved protocol called TED+ (trade-off energy with delay plus). This protocol is a combination of three improved approaches:

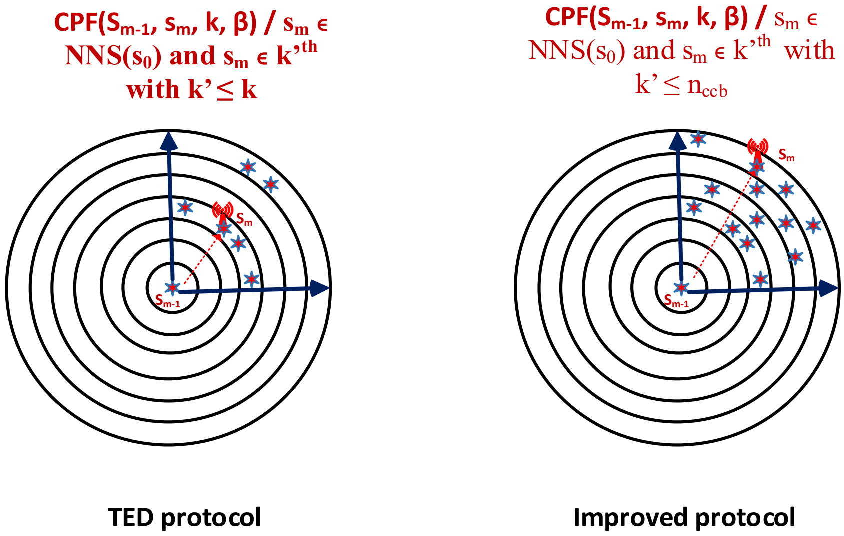


Fig. 4 Improvement by checking the condition at s_{m-1}.

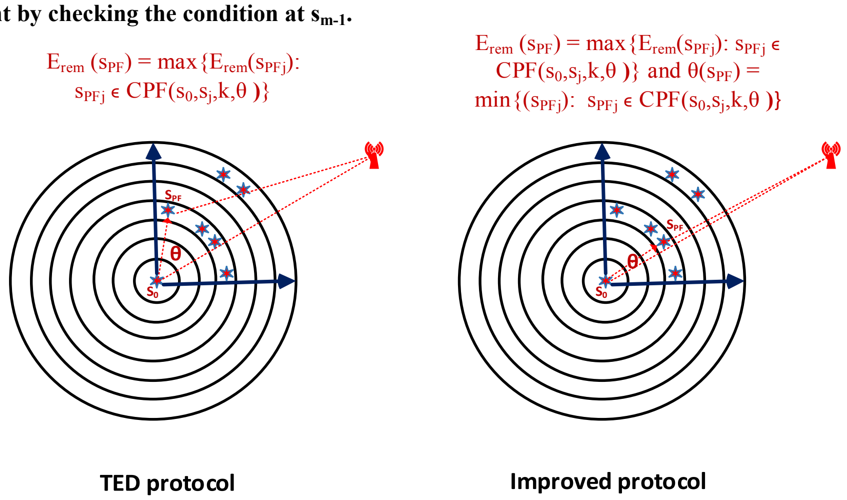


Fig. 5 Improvement by choosing minimum θ angle.

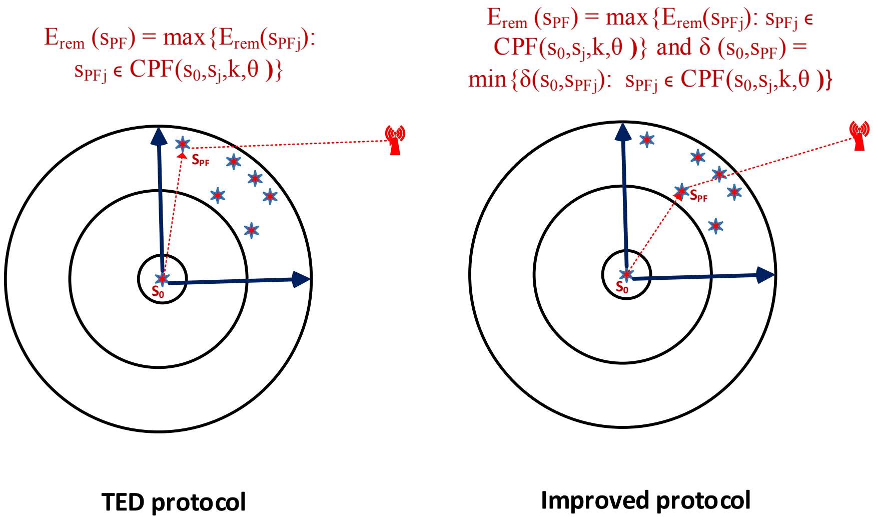
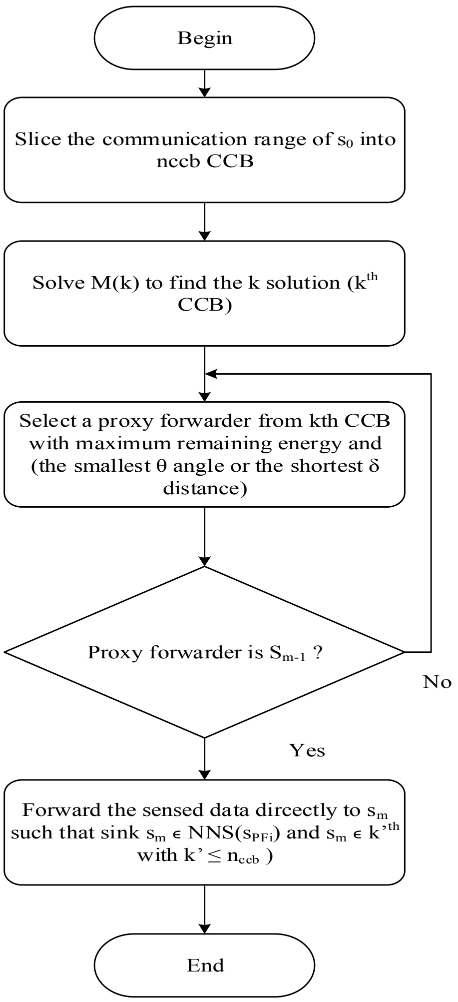


Fig. 6 Improvement by choosing shortest δ distance.

expand the selection area of candidate proxy forwarders at s_{m-1}, choose the smallest θ angle, choose the shortest δ distance.

Flowchart and Pseudo code of TED+ protocol:



Begin

// Actions executed by a source s_0

Pha 1: Slice the communication range $CD(s_0, R)$ of s_0

1. Slice $CD(s_0, R)$ into n_{ccb} CCB

Pha 2: Select an appropriate CCB using k

2. Select the appropriate weights $0 \le w_1, w_2, w_3 \le 1$ such that $w_1 + w_2 + w_3 = 1$ to solve the multi-objective optimization problem: Minimize M(k) $(0 \le k \le n_{ccb})$

3. Choose a CCB id, k, which is a solution to M(k)

4. If sink $s_m \in NNS(s_0)$ and $s_m \in k'^{th}$ with $k' \le n_{ccb}$ Then

Begin

5. Forward the sensed data directly to the sink s_m

6. Break;

End

7. Else

Begin

Pha 3: Select a proxy forwarder from k^{th} CCB

8. Identify a subset candidate proxy forwarders $CPF(s_0, s_m, k)$ from k^{th} CCB

9. If $CPF(s_0, s_m, k) = \emptyset$ Then

Begin

Randomly pick the closest q^{th} non-empty lower/higher CCB

10. $k = q$;

End

11. Determine the first proxy forwarder s_{PF1} such that

E_{rem} (s_{PF1}) = max{$E_{rem}(s_j)$: s_j ϵ CPF(s_0,s_m,k, $\boldsymbol{\theta}$)}

AND

($\theta(s_{PF1})$ = min{ $\theta(s_{PFj})$: s_{PFj} ϵ CPF(s_0,s_m,k, $\boldsymbol{\theta}$)}

OR

$\delta(s_i,s_{PF1})$ = min{$\delta(s_i,s_{PFj})$: s_{PFj} ϵ CPF(s_0,s_m,k, θ)})

12. Forward the sensed data packet to s_{PF1}

// Actions executed by any proxy forwarder

13. While (sensed data has not reached s_m) Do

Begin

14. If sink s_m ϵ NNS(s_{PFi}) and s_m ϵ k'th with k' ≤ n_{ccb} Then

Begin

15. Forward the sensed data directly to s_m

16. Break;

End

17. Else Replace s_0 with s_{PFi} and run steps 5-15

End

End

End

4. Simulation and Evaluation of Results

In this section, we used Matlab R2012b to simulate TED protocol and our TED+ proposed protocol. The input parameters using for simulation is in Table 1.

In the section 3, we clearly analyzed improvements of TED+. Because of optimizing energy consumption between two consecutive intermediate nodes, the total consumption energy of TED+ is better than TED's (Fig. 7). On the other hand, by optimizing the selection area of s_{m-1}, the delay of TED+ is lower than TED's (Fig. 8). Finally, the number of dead nodes after each round is also different between TED and TED+ (Fig. 9).

Two instances of TED are SR (short range forwarding) and LR (long range forwarding). Using SR, the sensors forward data over short distances. With LR, then sensors forward data over long distances. SR performs the best in terms of energy consumption, and hence, provides lower bound on energy (in simulation, using k = 1 or 2). LR performs the best in terms of delay, and hence, provides lower bound on delay (in simulation, using k = n_{ccb} or n_{ccb} -1). TED helps find a balance between energy and delay. TED+ performs a better balance than TED in terms of energy and delay (Figs. 10-12).

Table 1 Imput parameters using for simulation.

			α	W1	W2	W3
E_{elec}	*Electronics energy*	50pJ/bit	2	0.5	0.3	0.2
E_{fs}	Transmitter amplifier in free- space	10 pJ/bit/m^2				
E_{mp}	Transmitter amplifier in multi-path	0.013 pJ/bit/m^2				
a	Data size	256 bit				
λ	Spatial density	0.001 sensor/m^2				
c	Average delay per node.	0.001				
$\delta(s_0,s_m)$	Euclidean distance [s_0 , s_m]	3,500 m				
R	Communication range radius	350 m				
Area	Simulation area size	1,000×1,000				
Nodes	The number of sensors	500				

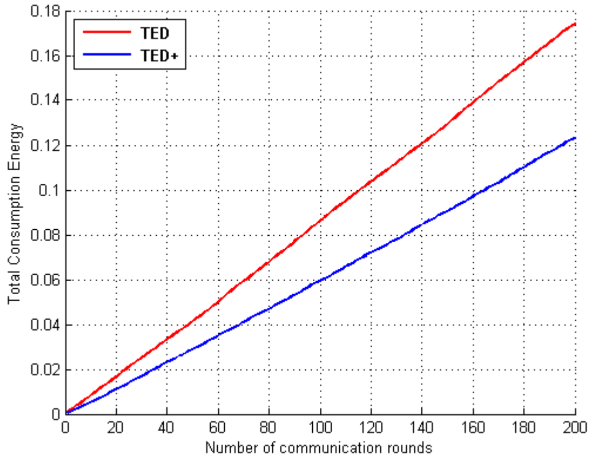


Fig. 7 The total energy consumption between TED and TED+.

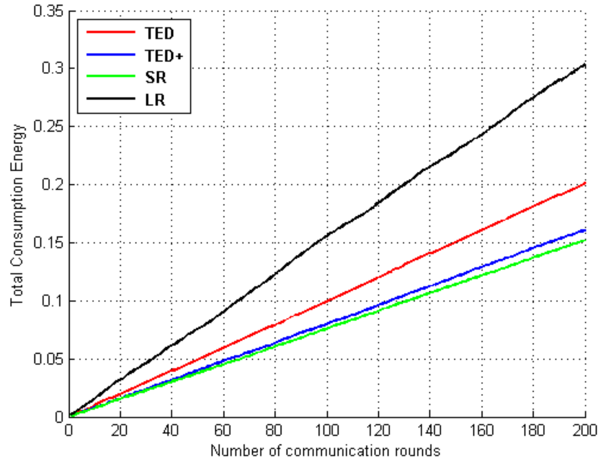


Fig. 10 Total consumption energy.

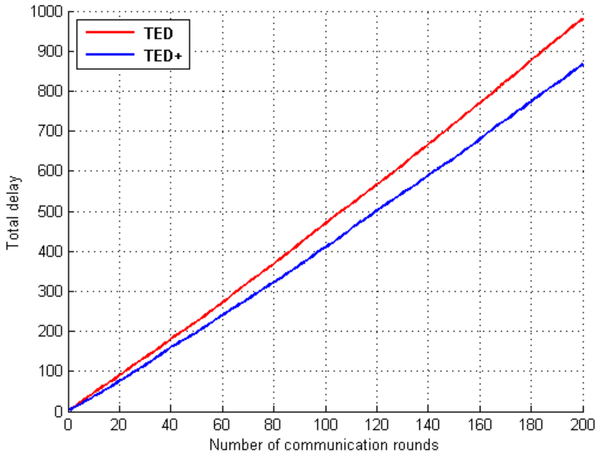


Fig. 8 The total delay between TED and TED+.

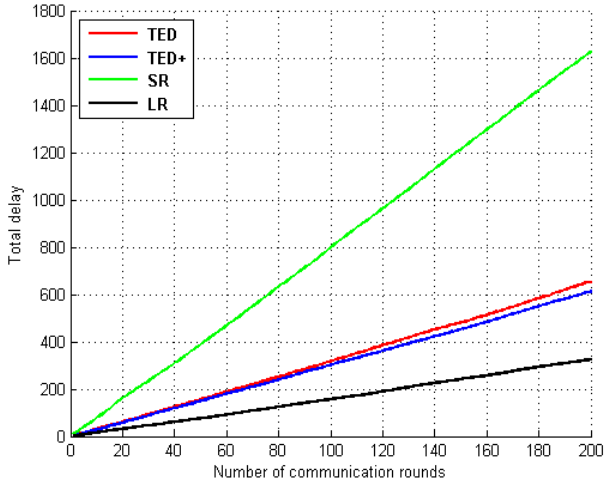


Fig. 11 Total delay.

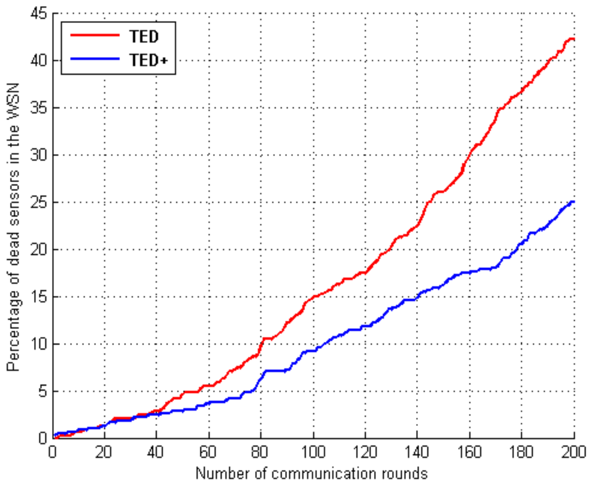


Fig. 9 The dead nodes between TED and TED+.

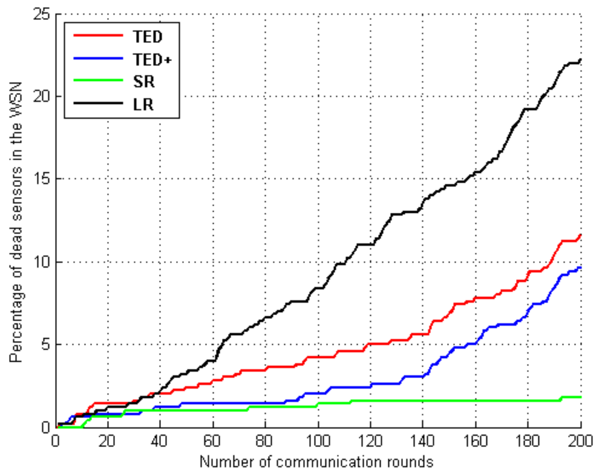


Fig. 12 Dead nodes.

5. Conclusion

The asynchronous consumption energy in WSN caused difficultly gathering information. The trade-off between three conflicting goals (energy consumption, delay and energy depletion) as a multi-objective optimization problem which is solved using a WES approach. Our paper studied TED protocol. Then we improved TED in terms of optimizing selection area of s_{m-1} such that $s_m \in k^{'th} / k' \leq n_{ccb}$, optimizing consumption energy of two consecutive intermediate nodes by choosing minimum $\theta = \angle s_1, s_0, s_m$ or choosing shortest $\delta(s_i, s_j)$ distance. The simulation results showed that our proposed protocol TED+ is more efficient than TED on energy and delay.

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