
I-Hui Li¹,², I-En Liao¹, Feng-Nien Wu³
¹Department of CSE, National Chung Hsing University, Taiwan
²Department of INSA, Ling Tung University, Taiwan
³Foxconn Technology Group, Taiwan
phd9301@cs.nchu.edu.tw, ieliao@nchu.edu.tw, fengnien@gmail.com

Abstract

With the improvement of miniaturized fabrication and battery technologies, the topic of deploying a wireless sensor network which uses tiny sensors with the abilities of detecting environmental factors and processing data is getting more and more important for different environments and applications. However, the resource limitation in a sensor brings out an important issue. The challenges for saving energy and thus extending the lifespan of a sensor are conceivable. This paper proposes a protocol involving multi-hops and self-organization of routing paths. The method, using time division with reservation scheduling, reduces energy consumption and prevents packet collisions. The routing decision takes the transmission cost, the battery status and the traffic load into consideration. This yields efficient routings and results in energy savings in sensors. The experimental results show that the system’s lifespan is extended dramatically while staying robust under different environmental parameters.

Keywords: Wireless sensor network, Energy-efficient protocol, Routing protocol, Traffic load, Scheduling.

1 Introduction

Wireless sensor networks (WSNs) have been increasingly deployed for a variety of applications, ranging from environmental monitoring, to battlefield surveillance, disease detection, animal migration [1], traffic or mobile monitoring [2], landslide warning, and so forth. WSNs are a particular type of ad hoc network [3] in which a large number of sensors are densely deployed within an environment of interest and used to report changes in this environment over time to a central base station (BS).

A sensor usually has a limited processing unit, small size memory, a sensing unit and a wireless communication transceiver [4]. It usually uses a small battery as the main energy supply and some sensors have solar cells as an auxiliary energy source [5]. A sensor can sense and detect the changes of targets in the environment, process the collected data and transmit the processed data to the data collection center or BS by wireless communication. Sensors with efficient protocols can do self-organization to form a specific network structure with high performance. The vehicle ad hoc network (VANET) [6-7] is the most conspicuous application. Each device (like a sensor) in VANET has a GPS and synchronization making it easy to perform a self-organization scheme.

In WSNs, the energy consumed by nodes depends on the frequency at which they transmit, and the distance over which they broadcast this data. As a result, the energy is rapidly consumed if the nodes are distant from BS or are required to communicate frequently with BS. Furthermore, the effects of data distortion and noise also increase as the transmission distance increases.

The limited resources in a sensor and the underlying load in-balance routing protocol between sensors pose a significant problem for not having sufficient energy for the sensor to have a reasonable lifespan. The challenges for saving energy and thus extending the lifespan of a sensor as well as that of WSNs are conceivable. This paper proposes a multi-hop routing protocol called Traffic Load-Aware Energy Efficient Protocol (TLAEEP). TLAEEP has dramatically reduced the waste of sensor energy and the probability of collision of packets by time division with reservation scheduling between sensors. This study used the accumulated energy load and traffic load information to choose the traffic load-aware routing paths on WSNs. As a result, the WSN bypasses low energy sensors and transmits by means of the traffic load-aware path to efficiently extend the lifespan of the whole WSN. By using the time division with reservation scheduling protocol, the WSN has the ability to prevent packet collisions. TLAEEP provides a compromised routing to achieve benefits of static and dynamic routings.

The organization of this paper is as follows. Section 2 reviews some related work on WSN protocols. Section 3 describes the system architecture and detail methods of TLAEEP, and Section 4 performs simulations and comparisons with other schemes. Finally, Section 5 summarizes the major contributions of the present study and provides some brief concluding remarks.
2 Related Work

The protocols on WSNs can be categorized in several ways [9]. One simple classification is flat and hierarchical protocols. In flat protocols such as Flooding [10], GSP [11], T-GSP [12], and TAEE [13], tasks and roles are all the same in each sensor. In hierarchical protocols the sensors on the network play different hierarchical roles. For example, a protocol using a clustering algorithm has a cluster-head (CH) to collect and aggregate the information in the group, such as LEACH [14], LEACH-C [15], EAP [16], and READY [17].

Flooding [10] is an earlier data transmitting method for directionless broadcasting. Each sensor broadcasts packets to the neighborhood and unless the packets have reached the destination sensor or the packet’s transferring maximum is reached, a receiving sensor broadcasts the data to the next neighbor after receiving the data unless the packets have reached the destination sensor or the packet’s transferring maximum is reached. Flooding topology and routing management are not complicated. Flooding has flexibility in setting up a network. However, it still has some problems when operating [10]. The main issues arise from three aspects: (1) Data Implosion; (2) Data Overlap and (3) Resource Blindness.

One of the experiments in this paper compares the proposed protocol to Flooding. This is because Flooding experiments is simple and easy. On the other hand, Flooding has no special controls for energy and traffic. Flooding is a good baseline for comparing different routing protocols.

Chung et al. [18] have proposed an efficient energy aware routing protocol which is based upon the on-demand ad hoc routing protocol. The protocol determines a proper path with consideration of node residual powers and hop count only. In GSP (Gossip-based Sleep Protocol) [11], a gossiping node employs a random variable to decide whether or not to enter sleep mode. However, putting nodes into sleep mode may interrupt the ongoing traffic. T-GSP (Traffic-aware GSP) [12] is proposed to improve GSP, which considered the ongoing traffic before changing the radio mode of a node.

TAEE (Traffic-Aware Energy Efficient) [13] exploits the information about the sensors’ traffic pattern in addition to power residue levels to optimize the load distribution of the WSN, and thus it accomplishes longer lifetime. The major contribution of TAEE is to introduce a new metric to quantify the prospective traffic load, and to use the metric in path determination. But there are some potential problems. (1) It needs global knowledge to run Floyd-Warshall algorithm; (2) The energy consumption does not consider the amount of data; (3) TAEE uses shortest-path spanning tree rooted at the sink for routing. Some sensors in the critical paths will drain out energy rapidly due to load in-balance.

LEACH (Low Energy Adaptive Clustering Hierarchy) [14] is a pioneering work of cluster-based protocols on WSNs. In a synchronized environment, LEACH has two phases. The first phase is setup phase in which each sensor follows a probability equation to determine if it is the CH. The sensor, which is a CH will send an ADV message to notify neighbors and cluster the WSN. The second phase is steady phase. In this phase each sensor in the cluster conforms to the time division multiple access (TDMA) schedule made by CHs. Each sensor transmits data to the CH in its own time slot. After a period of time, CHs do data aggregation and send the aggregated data to BS. LEACH-C [15] was proposed after LEACH. In LEACH-C, BS centralized controls the formation of clusters.

There are some potential problems with LEACH and LEACH-C. (1) A CH needs to store communication data about its cluster. Since all sensors may be CHs, storage cost increases. (2) A CH should be open all the time for communicating with the sensors in its cluster, which wastes more energy. (3) After deciding which sensor is the CH, the neighborhood of the CH joins this cluster. Therefore, the CH will approximately be in the center of the cluster, meaning some sensors nearer the sink will have a greater transmission distance. (4) The assumption that each sensor should directly communicate to BS is impracticable for real WSN environment.

By TDMA, the CH will allocate fixed and planned time slots for each sensor. Each sensor transmits only in its own time slot. This introduces some advantages: (1) avoiding most packet collisions; (2) enhancing the reliability of data transmission; (3) decreasing energy consumption; (4) and finally, achieving the traffic load balance.

Based on the advantages of TDMA, especially when sensors change in different states, sensors can follow the time division schedule to save energy and make use of the time slots efficiently when some sensor states are not in transmission mode. TLAEEP is a multi-hop protocol utilizing the merits of TDMA (similar to LEACH), but it adds a reservation scheduling mechanism to greatly improve energy savings and reduce packet collisions.

3 The Traffic Load-Aware Energy Efficient Protocol

TLAEEP is a protocol involving multi-hops and self-organization of routing paths. TLAEEP utilizes accumulated energy load and the traffic load for the routing decision. Firstly, TLAEEP considers both the shortest path and the remaining energy of sensors. Then, it filters the
traffic load for load balance further. This method, using
time division with reservation scheduling, prevents energy
consumption and packet collisions. The routing decision
takes the transmission cost, the battery status and the traffic
load into consideration.

3.1 System Architecture of a Sensor
A sensor can be composed of a TLAEEP module,
a sensing module, a wireless module, a data processing
module and an energy management module as in Figure 1.
The sensor module is in charge of sensing and collecting
environmental information. The wireless module
communicates by sending and receiving a wireless signal.
The data processing module processes the collected data.
It may preprocess, compress and aggregate the data. The
energy management module manages the energy supply
and monitors energy status. It usually works closely with
the wireless and data processing modules. When the sensor
is in sleeping mode, the energy module can shut down the
wireless module to save energy. The wireless module also
may adapt the wireless transmission energy for different
transmission ranges to reduce energy consumption.

Definition 1: A Target Sensor
A sensor T is called the target sensor of sensor S if T is
the next hop of S in the routing path from sensor S to the sink.

Definition 2: A TLAEEP Target Sensor
A sensor T is called the TLAEEP target sensor of
sensor S if T is chosen as the next hop of S in the routing
path from sensor S to the sink by the TLAEEP.

Definition 3: A Neighbor Sensor
A sensor T is called the neighbor sensor of sensor S if
T is within transmission range of sensor S.

Definition 4: A Message-Collecting Sensor
A sensor S is called a message-collecting sensor,
if sensor S is in message collection stage in which it is
receiving message from its neighbor sensors using the
message collection unit to determine its target sensor.

3.2 Operation of TLAEEP
In a synchronized environment, the operation of
TLAEEP is divided into rounds as LEACH. Each round
has two phases: the setup phase and the steady state phase.
It begins with the setup phase to decide all routing paths
by the message collection and routing units, and then the
sensed data will be transmitted in the steady state phase for
a fixed period of time. TLAEEP re-computes all routing
paths every round, which can then reduce the overhead of
dynamic routing and have better adaptability than static
routing. The flowchart of TLAEEP is shown as Figure 2.
3.2.1 Setup Phase

In the setup phase, the proposed protocol selects the TLAEEP target sensor of each sensor by the message collection and the routing units. The routing decision scheme regards the sink as the center of a circle shown in Figure 3. Starting from the sink broadcasting MEC (as described in Subsection 3.4.2), the system works outward with the transmission range of a sensor to find all TLAEEP target sensors in this circle, and so on, until all routing paths are decided. As in Figure 2, while the TLAEEP target sensor is found, each sensor performs its time division with reservation scheduling in the scheduling unit. The details of each unit are described in Subsection 3.3 to Subsection 3.5.

The duration of the setup phase should cover the time period in which all sensors can find their TLAEEP target sensors. This time period depends on the scale of WSN. If some sensor has not found its TLAEEP target sensor after the setup phase, it will be regarded as a dead sensor in this round.

Once the setup time expired, the system enters the steady state phase, as shown in Figure 2.

3.2.2 Steady State Phase

The operation of the steady state phase of a sensor is broken into frames, as shown in Figure 4. Each frame contains some fixed number of time slots, and every time slot has fixed time period for data transmission. All sensors transmit the sensed data to their TLAEEP target sensors at their allocated transmission time slots in TLAEEP target sensors. The received data is forwarded hop-by-hop along the routing path to the sink. Those sensors which are not at their turns for transmission can be turned off to save energy. After a period of time (a system parameter) for data transmission, the system goes into a new round, as in Figure 2.

Assume that all sensors are sensing the environment at a fixed rate and always have data to send, and then each sensor will transmit at least once in each round. A frame is a basic unit for a sensor to make schedule for receiving data from other sensors. A schedule is defined as the reservation results in a frame. A sensor transmits the data to its TLAEEP target sensor at most once per frame. And the maximum frequency of a sensor to transmit data is the number of frames in a round.

TLAEEP also assume that every sensed data for each sensor has the same size. Each sensor will receive data from other sensors according to the schedule, and send the received data and its own sensed data to its TLAEEP target sensor at its transmission turn. The duration of a time slot should cover the time period for a sensor to transmit its own sensed data. If a sensor is receiving data from other sensors, the duration of a time slot should be larger for transmitting those data. If data cannot be transmitted completely in a time slot, they will be transmitted in the latter frames. So, the duration of a time slot is determined by the application and scale of a WSN.

The number of frames in a round means the maximum number of transmissions that can be made by a sensor in a round. It should cover the number of concentric circles of the WSN as shown in Figure 3, for sensors in the outermost circle can send data to the sink at least once. And this still depends on the scale of a WSN.

In summary, the different WSN applications have different sensed data size, which will determine the duration of a time slot. The scale of a WSN decides the number of time slots in a frame and the number of frames in a round. Thus, the duration of the steady state phase in a round will be determined by each real WSN application.

3.3 Message Collection Unit

When a message-collecting sensor is switched on, it collects messages from neighbors to determine the TLAEEP target sensor before it does anything else. The collected messages are neighborhood information. Each neighbor sensor should provide information to the message-collecting sensor as in Figure 5, which includes sensor ID, energy status, the MEC (Minimum Energy Consumption) value, transmission schedule, the traffic load of each neighbor sensor, and distance between the message-
collecting sensor and this neighbor sensor. The energy status is the remaining energy of this neighbor sensor. The MEC value is a proposed quantity and the details are shown in Subsection 3.4. The energy status, the MEC value and the traffic load help to make a good routing decision. The routing and scheduling units utilize the collected messages which help determine the best routing and scheduling.

Assuming that each sensor knows its own location and energy status, a sensor can get its location at low cost from GPS or some localization systems [20]. Thus, distance between a sensor and its neighbor sensor can be calculated. Other neighborhood information is described in later subsections.

3.4 Routing Unit

The purpose of the routing unit is to select the traffic load-aware energy efficient target sensor for each sensor. There are three factors considered: (1) energy load; (2) shorter path; (3) traffic load. The routing decision scheme is introduced firstly in Subsection 3.4.1. MEC calculation includes factors (1) and (2) and is described in Subsection 3.4.2. Subsection 3.4.3 shows how to find the traffic load-aware energy efficient target sensor.

3.4.1 Routing Decision Scheme

In the beginning, the sink sends message to its neighbors. Each neighbor sensor, such as sensor T in Figure 3, receives message in its message collection unit and calculates its MEC value. Then each neighbor sensor of the sink sends its message to its neighbors, such as S in Figure 3. Such sensor’s routing unit uses the messages to select a TLAEEP target sensor by calculating the MEC values and considering the traffic load. It applies a reservation to the TLAEEP target sensor in the scheduling unit, and then TLAEEP target sensor modifies its schedule with reservation in its own scheduling unit. Finally, these sensors broadcast their messages to their neighbors, and the system repeats the above procedures until all routing paths are decided. The detail methods are in the following subsections.

3.4.2 MEC Calculation and Broadcast

TLAEEP used a first order radio model of wireless transmission like LEACH. This model provides the estimated energy in wireless transmission, the estimated transmission energy is:

\[ E_{tx}(l,d) = \begin{cases} \frac{1}{2}E_{elec} + le_{fs}d^2, & d < d_0 \\ \frac{1}{2}E_{elec} + le_{mp}d^4, & d \geq d_0 \end{cases} \]

\[ E_{tx}(l,d) \] is the required energy for transmission, \( l \) is data length and \( d \) is distance.

Inside of distance \( d_0 \), this study used a free space model. \( e_{fs} \) is the amplifier energy factor in a free space model. Beyond \( d_0 \), this study used a multipath interference propagation model. \( e_{mp} \) is the amplifier energy factor in the multipath interference propagation model. When receiving a wireless signal, the estimated energy is:

\[ E_{rx}(l) = lE_{elec} \]  

\( E_{rx}(l) \) is the required energy for receiving, \( l \) is the data length and \( E_{elec} \) is the consumed energy for per bit. This factor changes in different environments such as a wireless circuit or in data coding.

In this model, assuming that \( E_{elec} = 50 \text{nJ/bit} \), \( e_{fs} = 0.0013 \text{pJ/bit/m}^2 \), \( e_{mp} = 8.77 \text{pJ/bit/m}^2 \), which were used in the LEACH scheme. Then \( d_0 = 87.7 \text{m} \) can be derived from Equations (1) and (2).

\[ d_0 = \sqrt{\frac{e_{fs}}{e_{mp}}} \approx 87.7 \]

\( d_0 \) is not a large number. If sensors can communicate directly to the sink, such as LEACH and LEACH-C, the transmission distance can easily exceed \( d_0 \). As a result, the multipath interference propagation model would usually be adopted due to many long distance transmissions. Thus the WSN energy consumption is great. The outdoor range of the MICA2 [21] (a third generation mote supplied by Crossbow Technology Inc.) is only 500 feet (about 152.4 m). Consequently, the CHs in LEACH and LEACH-C consume a significant amount of energy, and may even be unable to transmit directly to the BS in a real environment.

Therefore, TLAEEP adopted multi-hop routing to avoid the multipath interference propagation model. The proposed protocol uses energy load as a primary factor for considering transmission cost when deciding routing. Using this concept, TLAEEP balanced the evaluation by considering both energy consumption and energy load for modifying the routing in order to reach the goal of extending the lifespan of the WSN. The energy load equation is as follows:

\[ EW_{st} = \frac{E_{tx}(d_{st},l) + E_{rx}(l)}{PL_{st}} + PL_{st} \]

\( EW_{st} \) is the energy load when sensor \( S \) transmits data to sensor \( T \). \( d_{st} \) is the distance between \( S \) and \( T \), \( l \) is the data length, \( PL_{st} \) and \( PL_{st} \) are the remaining energy levels of sensors \( S \) and \( T \) respectively.
Wireless transmission energy is strongly affected by the transmission distance. Long distance transmission consumes more energy and short distance transmission consumes less. However, to finding the shortest path, a sensor usually needs global knowledge. But it is not easy for each sensor to get global knowledge.

Making a MEC route can solve both the best path decision and the problem of transmission direction selection; it can also find routing paths without global knowledge. While each sensor collects the information nearby, it gets MECs broadcasted by other sensors. A MEC value broadcasted by sensor T is denoted by MEC(T), which represents the Minimum Energy Consumption from sensor T to the sink. If a sensor gets such message, it is the message-collecting sensor, for example, S. It then merges the transmission energy load from S to T. After that, the value is the total estimated energy load for a message-collecting sensor. From among the neighbors, the message-collecting sensor S chooses a sensor with the minimum sum of MEC and energy load (EW) as the routing target sensor. Equation (5) shows MEC calculation.

Assume T is a sensor that broadcasts its MEC to the message-collecting sensor S. NB(S) is a set that includes all neighbors of sensor S.

\[
\begin{align*}
\text{MEC}(\text{Sink}) & = 0 \\
\text{MEC}(S) & = \min(\text{MEC}(T) + \text{EW}_{ST}, T \in \text{NB}(S)) \quad (5)
\end{align*}
\]

TLAEEP makes better routing decisions by MEC values. Through broadcasting MEC values, TLAEEP can calculate the MEC values of all sensors. At first the MEC is broadcasted from the sink to its neighbors. Then the neighbors utilize Equation (4) and (5) to accumulate MEC step by step until all sensors have MEC values.

This MEC broadcasting scheme forms concentric circles in a WSN, and the transmission range of a sensor is the radius. Figure 6 shows the MEC broadcast. The double circles node is the sink. For simplicity, assuming all EW is 1, so each MEC accumulation increases by 1. Instead of getting information from some centralized sensor, each sensor receives information from the MEC broadcasting of its neighbors. Therefore, TLAEEP can determine the target sensor by means of MEC without global knowledge.

Due to the limitation of the transmission range in a sensor, the sensors closed to the sink will consume their energy rapidly in most multi-hops protocols and eventually bring down the system when the energy of those sensors are exhausted. TLAEEP re-computes all routing paths at each round. As a result, it can relieve the sensors with heavy loads in the previous round. Therefore, the MEC broadcasting scheme in TLAEEP can balance the load of sensors closed to the sink to prolong the lifespan in the whole system.

**Lemma 1.** The Best Target Sensor T for Message-Collecting Sensor S is the Sensor with the Minimum Sum of MEC(T) and EW_{ST} in S’s Neighbor Sensors.

**Proof:** From Equation (5), the lesser sum of MEC(T) and EW_{ST} of the neighbor sensor T is, the minor MEC(S) is. If MEC(T) was small, the minimum energy consumption from sensor T to the sink is smaller than other neighbors. Thus, the load of target sensor T is low. From Equation (4), if EW_{ST} is low, the message-collecting sensor and the target sensor have more remaining energy. Selecting such a target sensor T will keep load balance to prolong the whole system lifespan. Moreover, the transmitting energy to get from sensor S to the target sensor T is less. This will reduce transmitting energy consumption. By considering all the above factors, choosing the sensor T with the lowest sum of MEC(T) and EW_{ST} among the neighbors is the way to determine the best target sensor of sensor S.

**Definition 5: Transmission Direction Selection Problem**

The transmission direction selection problem in a WSN means that a sensor may select a target sensor for the next hop that is farther from the sink. As shown in Figure 6, all neighbors are candidates for the next hop from sensor S. Sensor S could select sensor T which is closer to the sink. But, if sensor S selects sensor C or D which are farther from the sink, more transmission energy is consumed than if it selects sensor T.

**Lemma 2.** Selecting the Minimum MEC Value from Among Neighbor Sensors as the Target Sensor does not Incur the Transmission Direction Selection Problem.

**Proof:** As the MEC value is broadcasted from the sink to its neighbors, the sensors accumulate MEC values step by step until all sensors have MEC values. This scheme forms concentric circles in a WSN, as shown in Figure 6, and the transmission range of a sensor is the radius. Thus, the
farther a sensor is from the sink the larger its $MEC$ value. In our routing decision, a sensor chooses the sensor having the lowest $MEC$ value as the target sensor from among its neighbors. A sensor will not select a target having a larger $MEC$ value than its own. Thus, there would be no transmission direction selection problem.

Incidently, the $MEC$ value broadcast scheme can prevent the system from a routing cycle.

In a near traffic load balanced and uniform deployed WSN, if delay time of a packet is defined as the time in which a packet is transmitted to the sink. The average delay time of a packet will be $t^*(K + 1)/2$, which is proved in Lemma 3.

Lemma 3. Assume that at the End of the Setup Phase, $K$ Concentric Circles are Formed; Each Track has $n$ Sensors; and the Transmission Time Between Two Neighboring Tracks is $t$. The Average Delay Time of the Whole WSN is $t^*(K + 1)/2$.

Proof: If the tracks in concentric circles are numbered from 1 to $K$ beginning from the inner-most track, then the delay time for the sensor in track $i$ will be $t^*i$. The average delay time of transmitting a packet to the sink is calculated as $n^*t^*(1 + 2 + \ldots + K)/n^*K = t^*(K + 1)/2$.

Because $MEC$ broadcasting scheme does not generate the transmission direction selection problem as proved in Lemma 2, $MEC$ values of the sensors in the outer track will be larger than those of the inner track. A sensor will select a TLAEEP target sensor in the track with one step closer to the sink. So, the number of concentric circles can determine the maximum delay time in the entire WSN, through $MEC$ broadcasting scheme in TLAEEP.

3.4.3 Traffic Load-Aware Energy Efficient Routing

From the routing decision, TLAEEP chooses the target sensor of a message-collecting sensor. A target sensor may have the shorter routing path and better energy load, but if its own remaining energy cannot support the transmission or if the traffic load is extremely high the sensor will be excluded. If a sensor meets the requirements of supporting transmission and an under-control traffic load, TLAEEP chooses it as the TLAEEP target sensor.

In TLAEEP, each sensor has its own schedule consisting of time slots for receiving data from other sensors. Each time slot has fixed time period for data transmission. A sensor must make time-slot reservation from the receiving sensor before transmission. At its turn for transmission, a sensor can transmit its own sensed data and the data received from other sensors. According to the description in Subsection 3.2.2, a sensor can send at most once in a frame, and there are many frames in a round, if the demand transmission data could not be completely sent in a frame, they would be transmitted in the latter frames.

The duration of a time slot determines the maximum amount of data received or for one transmission. All received data should be sent to the next hop. The maximum sensing rate of a sensor in a round is that a sensor senses once in each frame. Assume that the maximum amount of data transmitted of a time slot is $m$, the size of one sensed data is $n$, and there are $r$ reserved time slots in a frame and $k$ frames in a round. The amount of data transmitted by the sensor will be $(r^*m + n)^*_k$.

As the discussion in Subsection 3.2.2, the duration of a time slot should cover the transmission of one sensed data. Therefore, $m$ is larger than $n$. And the sensing frequency may be less than the number of frames in a round. For simplicity, assuming that $n$ is equal to $m$. Then the upper bound for the amount of data that will be sent by a sensor in a round is $(r + 1)^*m^*k$, and this value represents the maximum transmission amount of data or bandwidth for a sensor. The minimum transmission amount of data of a sensor is $1^*m$. And the traffic load of a sensor can be regarded as the data transmission rate in a round.

As a frame is a basic unit for a sensor to make schedule for receiving data from other sensors, a schedule is the reservation results in a frame, the reservation rate of the time slots within a frame is then used as an indication of the traffic load.

Definition 6: Traffic Load of a Sensor

The traffic load (TL) of a sensor represents the amount of data that will be sent by the sensor. If the maximum amount of data transmitted of a time slot is $m$, and there are $s$ time slots and $r$ reserved time slots in a frame. The traffic load of a sensor is defined as the ratio of the reserved time slots of the sensor in a frame added by one to the number of time slots of a frame. It can be represented as

$$TL = \frac{(r + 1)^*m}{s^*m} = \frac{r + 1}{s}$$

(6)

An example is shown in Figure 7. There are 2 reserved time slots in a sensor’s schedule. Then the traffic load of this sensor is $(2 + 1) / 6 = 0.5$. If the number of frames is 3 in a round, the maximum transmission amount of data or bandwidth will be $(6 + 3)^*m$.

![Figure 7 An Example Schedule of a Sensor in a Round](image)

Figure 7 An Example Schedule of a Sensor in a Round
For finding the TLAEEP target sensor, energy load of the message-collecting sensor, and the traffic load of its target sensor are considered. Thus, the MEC value and the traffic load are two factors in our decision. TLAEEP regards the MEC value as the principal routing decision factor when a sensor has a smaller traffic load in a traffic-balanced network. When the traffic load of a sensor is larger than that of another sensor over Traffic Load Tolerance, TLAEEP chooses another low traffic load sensor that has a higher MEC value for routing. The TLT threshold is depended on the MEC value for routing. The TLT threshold is determined on WSN applications.

Assume \( T \) is a sensor that broadcasts its MEC value to the message-collecting sensor \( S \). \( T(T) \) represents the traffic load of \( T \). \( MEC(T) \) denotes the MEC value of \( S \) based on the MEC value of \( T \). \( NB(S) \) is a set that includes all neighbors of \( S \). In our network traffic design methodology, TLAEEP normally chooses a sensor \( T \) for routing when the sensor has low to medium traffic load. When the difference of traffic load between one sensor and other sensors exceeds TLT threshold, the probability of being a selected routing sensor is low since it has more amount of transmitted data.

\[
T \in NB(S) \text{ and } MEC(T) \leq MEC(S) \quad (7)
\]

Also, TLAEEP gives the constraints as in Equation (7), which ensures that sensor \( T \) is closer to the sink than sensor \( S \). There would be no transmission direction selection problem while selecting a TLAEEP target sensor of sensor \( S \). An example is shown in Figure 8; a sensor (source, denoted by \( S \) in the following) tries to choose the next transmission target sensor from its neighbors. The top two candidate sensors sorted by MEC value are \( S1 \) and \( S3 \) respectively. Assume that \( MEC(S) \) is less than \( MEC(S) \). The width of a line represents the traffic load. If two routes don’t have much difference in traffic load, the source will choose \( S1 \) as the next target. However, if the difference in traffic load is over TLT threshold, even though \( MEC(S) \) is larger, \( S \) will choose \( S3 \) as the TLAEEP target sensor.

The detailed algorithm is shown in Figure 9. The way to make a TLAEEP routing decision for a sensor is to sort the neighboring sensors in ascending order according to the MEC values. Then, based on the traffic load, the routing unit of a sensor will swap two sensors if the difference of traffic load between these two sensors is greater than TLT threshold. This process will result in the best routing target node appearing at the top of the list. As a result, the proposed routing algorithm can balance the energy consumption and traffic load of sensors.

\[
\text{SELECT_TLAEEKLargetar}t(NB_{\text{list}})
\]

\[
\text{Sort}_\text{by}_\text{MEC}(NB_{\text{list}})
\]

\[
\text{for } i=1 \text{ to } (\text{length of NB}_{\text{list}} - 1) \text{ do}
\]

\[
\text{for } j=1 \text{ to } (\text{length of NB}_{\text{list}} - i) \text{ do}
\]

\[
\text{if } (\text{NB}_{\text{list}}[j].\text{TL} - \text{NB}_{\text{list}}[j+1].\text{TL}) > \text{TLT threshold} \text{ then swap(}\text{NB}_{\text{list}}[j], \text{NB}_{\text{list}}[j+1]\text{) end if}
\]

\[
\text{end for}
\]

\[
\text{return neighbor}_{\text{list}}[1]
\]

3.5 Scheduling Unit

A good scheduling scheme helps to reduce energy consumption by controlling the timing of switching wireless energy on and off. Flexible adaptive scheduling can make on-demand bandwidth available. TDMA makes great use of the advantages of planned scheduling. That is, scheduling can both prevent collision and estimate the traffic load.

After the TLAEEP target sensor being decided, the message-collecting sensor makes an appointment with the TLAEEP target sensor to reserve time slots for scheduling. This paper adapts a TDMA-like protocol. Unlike TDMA in which only a central node has complete scheduling information, TLAEEP let each sensor have its own scheduling. As described in previous sections, a frame is a basic unit for a sensor to make schedule for receiving data from other sensors. A schedule is defined as the reservation results in a frame. The schedule is open for other sensors to reserve time slots for their own requests, not controlled by a central node. To enable neighbors to make better decisions, each sensor provides its own related information to its neighbors. Through the message collection unit, each sensor receives information from all its neighbor sensors to make an appropriate schedule in the scheduling unit.

After a sensor determines the TLAEEP target sensor, it sends out a time slot reservation request to the TLAEEP target sensor.
target while the TLAEEP target’s wireless receiver is switched on. Before reserving the time slot, the sensor checks the collected schedule of the TLAEEP target sensor and chooses a time slot which does not conflict with its own schedule. This prevents repetitive communications between source and target when the reserved time slot is unavailable. The request includes its own ID and the time slot reserving number, etc. The TLAEEP target sensor considers the request and decides to allocate the requested time slot for the source or not. If the TLAEEP target sensor cannot allocate reserved time slots, it sends a reject response message and its current schedule to the source, and the source sensor should then re-reserve another time slot and request again. Lastly, the TLAEEP target sensor sends a successful response message to the source indicating the result. As a sensor transmits the data to its TLAEEP target sensor at most once per frame in the steady state phase, each sensor can reserve one time slot only in the schedule of its TLAEEP target sensor.

While all routing paths are found and all schedules are planned, each sensor sends the sensed data to its TLAEEP target sensor according to its scheduling and by multi-hop routing until it returns to the sink.

4 Experimental Results

The simulator simulated LEACH, Flooding and TLAEEP protocols. Two implementation versions of LEACH named as LEACH_r and LEACH_p were compared with the other protocols. LEACH_r is a version of LEACH, which only relays data in the CH without any data aggregation. LEACH_p is a perfect data aggregation version of LEACH. Perfect data aggregation, as defined by W. Heinzelman et al. [15], means that no matter how many individual data are received from all sensors in a cluster, the CH can aggregate them into one single representative set of data.

Basically, most parameters referred to corresponding values in LEACH for fair comparison. The simulator considered BS was located at (0 m, 0 m). Each sensor was assigned an initial energy of 2J, each data message was 500 bytes long, and the data was 512 bytes long. Transmission range of a sensor was 100 m. The time period of the setup phase was 2 seconds. The number of time slots in a frame was 10, and a round consisted of 10 frames. Thus, there were 100 time slots in the steady state phase. The duration of a time slot was 0.5 seconds, and the time period of the steady state phase was 50 seconds. TLT threshold was 0.7. The energy for data aggregation in LEACH_p was set as 5 nJ/bit/signal. TLAEEP ran 50 rounds in each simulation.

The average survival time was measured in our simulations. The survival time of a sensor was defined as the length of the time period from the beginning operation of the sensor to the death of the sensor or the death of the WSN system. The death of the WSN system was the time when no message can reach the sink. The average survival time was the average of the survival time of all sensors.

The first simulation tested the performance of each protocol with different distribution ranges. There were 50 sensors distributed over the range of 50 × 50 m² in the beginning; then the area was extended an additional 50 m in both length and width. The results are shown in Figure 10. The average lifespan of TLAEEP reduces slowly and steadily as the distribution range increases. LEACH_r and LEACH_p are stable up to 100 × 100 m², but beyond that the average lifespan decreases dramatically. When it extends an additional 50 m in both length and width, the average lifespan falls to the one-quarter the initial values. At an additional 100 m the lifespan is almost zero. Finally, Flooding always shows poor performance.

![Figure 10 Different Distribution Area](image-url)

The second simulation kept the same size of distribution area and sensor density (50 sensors), but changed the shape. The experiment extended the length of the distribution area, but shortened its width. The shape of the distribution area became a thinner but longer rectangle. The results are shown in Figure 11. The X-axis stands for the length of the distribution area and the width is 100 × 100 m² divided by the length. The Y-axis stands for the average lifespan of the WSN.
TLAEEP has the average lifespan which reduces slowly and steadily. This means TLAEEP is influenced only by the average transmission distance but not sensitive to the shape of the sensor distribution. So when the distribution length is 400 m, the network still has an acceptable average lifespan achieved by the routing decision method controlling the transmission load of each sensor.

From the results of the first simulation, this study found that 100 × 100 m$^2$ is suitable for LEACH. So this distribution range size is used with shape reforming to evaluate the performance of LEACH. Compared to the first simulation, there are some differences. In the first simulation, the density of sensors diminishes as the range size grows. It greatly affects the performance of LEACH which relies heavily on data aggregation. In the second simulation the density of the sensors is constant. The rapidly descending trends of the average lifespan using LEACH$_r$ and LEACH$_p$ are caused by the increase in the average transmission distance which dramatically consumes transmission energy due to the interference of multipath. From simulations one and two, LEACH is sensitive to transmission distance. If the transmission distance is over 100 m the lifespan falls quickly. The performance of each protocol was measured in the third simulation by modifying the density of sensors while keeping the distribution area fixed. There were 50 sensors distributed over the range of 200 × 200 m$^2$ in the beginning; then the number of sensors was increased an additional 50 each time, until it was 400. Theoretically, the lifespan of the WSN should be longer. But high density brings a high probability of packet collisions. So, for checking the influence of sensor density, the experiment excluded the effect of packet collisions in simulation. The results are shown in Figure 12.

The lifespan curve of TLAEEP gradually increases as density increased. Although there is a big difference between LEACH$_p$ and TLAEEP at 400 sensors, LEACH$_p$’s efficiency for extending average lifespan is better than TLAEEP’s. The average lifespan using TLAEEP is 8.25 times longer than using LEACH$_p$ with 50 sensors. However, with 400 sensors it is only 1.53 times better than LEACH$_p$. This means data aggregation plays an important role in this result with a high density of sensors. Therefore, the energy saved will be proportionate to the density of sensor distribution. When the number of sensors is 8 times more, the lifespan is almost 8 times greater. When data is not aggregated, LEACH$_r$’s curve is a relatively flat line. For the same reasons mentioned previously, Flooding performs poorly.

The fourth simulation tested the effect of traffic load-aware mechanism. The high power capacity nodes had low energy load, that is, their MEC values were smaller. Such sensors have high priority to be selected as the TLAEEP target sensors. Therefore, the traffic load of these sensors will rise, and result in increasing the packet collision probability in these sensors. This problem can be alleviated by TLAEEP.

From the above, some high power capacity sensors are used to evaluate the performance of packet collision reduction for TLAEEP. There were 150 sensors distributed over the range of 100 × 100 m$^2$. Each sensor is assigned an initial energy of 1J, and 1 to 8 sensors are assigned an initial energy of 2J for high power capacity nodes. The number of collisions reduced is calculated by the difference of the number of collisions between TLAEEP and TLAEEP without traffic load-aware mechanism. The results are shown in Figure 13. The average number of collisions reduced is greater than 52 from the simulation.
results. There is no obvious relation between the average number of collisions reduced and the number of high power capacity sensors. The first reason is that the positions of these high power capacity sensors will affect the simulation results. The positions of these high power capacity sensors are randomly deployed in this simulation. If two or more such sensors were too close, the high priority candidate TLAEEP target sensors are almost always high traffic load sensors. Even though, TLAEEP will change the priority, it would not offer great help. Therefore, the performance of packet collision reduction is not stable. And the number of collisions reduced strongly depends on how the randomly selected high capacity nodes distribute over the WSN.

Secondly, the time division with reservation scheduling between sensors in TLAEEP can prevent most packet collisions with low traffic load. Most collisions may happen only when the reserved time slots are full. Thus, the improvement of packet collisions reduction by traffic load-aware mechanism is not great. However, TLAEEP can reduce packet collisions by scheduling and traffic load-aware mechanisms.

TLAEEP should perform the MEC value calculation and broadcasting, traffic load computing, and scheduling. From experimental results, the proposed TLAEEP does increase the average survival time of WSN and reduce the average number of packet collisions.

5 Conclusions

This paper proposes a traffic load-aware energy efficient protocol: TLAEEP. With the proposed routing decision method which introduces the accumulated energy load and estimated traffic load on a WSN. A WSN can have transmission by a shorter path and at the same time protect lower energy sensors and further achieve better load balance. In scheduling, the TLAEEP provides TDMA with reservation scheduling between sensors. It reduces energy consumption of sensors and prevents packet collisions. Scheduling can both prevent collisions and estimate the traffic load.

Experiments show that these two design features not only extend the lifespan of a WSN dramatically but also show good accommodation with different sensor distributions. In the future, we will do more research about data aggregation and multi-path routing on TLAEEP.

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**Biographies**

**I-Hui Li** received the MS degree in Computer Science and Information Engineering from National Chiao Tung University, Taiwan, in 1995. She is currently pursuing her PhD degree in the Department of Computer Science of National Chung Hsing University, Taiwan, and a lecturer in the Department of Information Networking and System Administration of Ling Tung University, Taiwan. Her research interests are in data mining, and wireless networks.

**I-En Liao** received the PhD degree in Computer and Information Science from the Ohio State University in 1990. He is currently a professor and chairman of the Department of Computer Science and Engineering of National Chung Hsing University, Taiwan. His research interests are in data mining, XML database, and wireless networks. He is a member of the ACM and the IEEE Computer Society.

**Feng-Nien Wu** received the BS degree in Information Engineering from Feng-Chia University, Taiwan, in 2005, and MS degree in Computer Science and Engineering from National Chung Hsing University, Taiwan, in 2007. He is currently an engineer in Foxconn Technology Group. His research interests are in data mining, optimization, and wireless networks.