Avoiding Heterogeneous Interference through Dynamic Routing in Wireless Sensor Networks

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Abstract—**Interference between WSN and other heterogeneous wireless networks, such as WiFi, Bluetooth et al, is a growing problem. Heterogeneous Interference (HI) may cut down reliability and throughput, as well as increase energy consumption. From the viewpoint of routing protocol, heterogeneous interference leads to frequent change of network topology and some nodes become isolated. Traditional routing algorithms are lack of appropriate interference control scheme in the heterogeneous interference environment. There always have such problems as complex technical cost, large overhead and poor performance. HI-Aware Dynamic Routing (HIADR) algorithm is capable of bypassing the strong heterogeneous interference sources and considerably utilizing nodes affected by weak interference or without any interference so as to improve the overall performance in WSN. Utilizing the concept of potential in classical physics, HIADR is designed through constructing a hybrid virtual potential field using depth and HI intensity to force the packets to steer clear of obstacles created by heterogeneous interference. Employing the RSSI-based interference estimation mechanism, HIADR can bring only a small amount of computational overhead on the local nodes. The experimental results show that HIADR can effectively avoid heterogeneous interference so as to improve the overall packet reception rate and forwarding load balance as compared to CTP.**

Keywords—Heterogeneous Interference; Dynamic Routing; Wireless Sensor Networks

I. INTRODUCTION

With the development of wireless communication technology, the demand for spectrum resources increases from different systems. ISM band becomes more and more crowded. Heterogeneous wireless communication systems which use both IEEE 802.11 and IEEE 802.15 series protocol standards and even Microwave are all in this band [1]. Hence, if the systems use the overlap band, it is easy to induce interference between them. When various wireless networks coexist in a region, some nodes in WSN will undergo the heterogeneous interference caused by transmission among end hosts in other networks. This interference is dynamic and non-persistent. It depends on when and how much traffic is generated by applications. In addition, this heterogeneous interference only imposes on partial nodes in WSN. Since redundant resources are available in WSN, we can utilize them to deal with the heterogeneous interference. Therefore, we can design an interference-aware routing for WSN, which can dynamically choose the nodes disturbed by weak heterogeneous interference, or even without any external interference. In this way, on the one hand, WSN can coexist with other heterogeneous wireless networks, on the other hand, the negative impact caused by heterogeneous interference can be constrained as much as possible. Base on this idea, HIADR is proposed to route packets around the strong interference areas and scatter packets along multiple paths consisting of weak or no interference affecting nodes. Utilizing the concept of potential in classical physics, HIADR is designed through constructing a hybrid virtual potential field using depth and HI intensity to force the packets to steer clear of obstacles created by heterogeneous interference. Employing the RSSI-based interference estimation mechanism, HIADR brings only a small amount of computational overhead on the local nodes. The cornerstone of HIADR is to construct two independent potential fields using depth and HI intensity respectively. The depth field would find the shortest paths. Once HI estimation grows over a certain threshold, which always means the presence of heterogeneous interference, the packets would flow along other suboptimal paths. Thus, the HI intensity potential field endows interference avoiding solution, and the depth field provides the basic routing backbone to forward the packets to the sink. These two fields will be combined into a hybrid potential field to dynamically make routing decisions.

II. BACKGROUNDS AND MOTIVATION

Electromagnetic spectrum can be used to solve heterogeneous interference issues. One classical method is spectrum analysis and the other is channel analysis. Mahmood et al. estimated interference through occupied time and space as well as the energy levels of the channel, and then a channel rating algorithm is constructed [2]. Noda et al. used effective scanning time to monitor channel energy and described the strong correlation of measurement results with the PRR [3]. These methods attempt to analyze interference from the perspective of the electromagnetic spectrum, and then intend to distinguish different characteristics of interference, and eventually hope to find a profound understanding. These explorations promise the future research direction, but the existence technique is complicated yet and the cost is high in current stage, thus can't be applied in practice.

Designing the proper network protocol is alternative approach to solve heterogeneous interference issues. The typical schemes include link quality estimation and optimizing MAC protocol. In [4], the link quality optimizing and weighting is employed for channel hopping. Link quality estimation can alleviate interference influence, but cause poor performance and introduce large overhead. C. M. Liang et al. used Multi-Headers (MH) and Forward Error Correction (FEC) technology to reduce the packet loss caused by the IEEE 802.11 interference [5]. Jeong et al. proposed a cluster-based structure whose cluster head is compatible with both IEEE 802.11 and IEEE 802.15.4 standard, and then the adaptive packet aggregation and scheduling algorithms are used [6]. MAC layer solutions can reduce packet loss caused by interference, but increase the burden of MAC layer protocol and limit the requirements of application due to the special packet structure.

However, dynamic routing technique could be a better choice to alleviate interference so as to decrease the additional cost and obtain a more effective and practicable interference control scheme for WSN. Fig.1 intuitively illustrates our motivations. Normally, source node sends packets on its shortest path. The shortest path is Source->4->2->Sink illustrated in Fig.1. Once WiFi AP starts exchanging message to smart phone, some nodes will suffer interference seriously, such as node 2, 4, 9, and some nodes mildly, such as node 6, 7, 8. In this case, the shortest path is heavily disturbed by heterogeneous interference due to wireless communication between WiFi AP and smart phone. If the packets in WSN are still forwarded along the shortest path, they will likely be disrupted by relatively strong heterogeneous interference, and eventually deteriorate the packet reception rate on the sink node. The energy is wasted due to packet transmission on the unreliable wireless link. Based on this observation and insight, the basic idea of our HIADR algorithm is to take the interference status on its neighbors into account, scatter subsequent packets on an appropriate detour path consisting of weak or no interference affecting nodes, for example, the detour path Source->5->3->1->Sink as illustrated in Fig.1. Otherwise, when the message exchange between WiFi AP and smart phone terminates, and correspondingly heterogeneous interference disappear, the shortest path from source node to the sink in WSN can naturally recover. Under this heterogeneous interference-aware dynamic routing paradigm, various wireless networks, such as WiFi, Bluetooth and WSN, can concordantly coexist, and the mutual interference between WSN and other wireless network is constrained as much as possible. The necessary condition of achieving this goal by employing the HI-aware dynamic routing is that there are redundant resources, moreover, should be properly utilized. Obviously, the packets on the detour path will experience a relatively large end-to-end delay. Anyway, the objective of our HI-aware dynamic routing is to avoid interference and improve PRR and forwarding load balance by distributing packets in space. To achieve this goal, we will borrow the concept of potential in classical physics to design a HI-aware dynamic routing scheme for WSN.

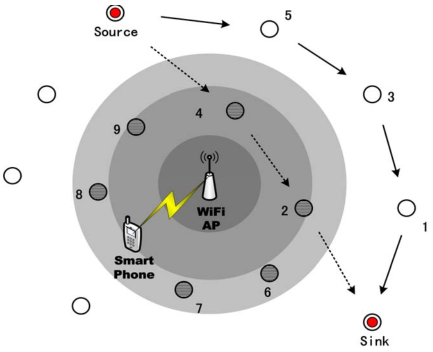


Fig. 1. Motivation example.

III. HI ESTIMATION ALGORITHM

In this section, we will explain the basis of RSSI as the HI measurement indicator, and then introduce the basic HI estimation model underlying the proposed HIADR scheme.

A. HI Measurement Indicator

The key point during designing HI-aware dynamic routing is how to identify and quantify heterogeneous interference. RSSI, which can be obtained directly from the RF module, is a good reaction out of the wireless interference. We measure heterogeneous interference with RSSI in 3 experimental scenes, which are no interference, WiFi interference and microwave interference environments, respectively. Experimental parameters are set as Table I, and the results are shown in Fig.2.

Observing Fig.2, we can see that the average value of RSSI is substantially at about -95 dbm in the case without interference, but it remarkably increases to about -60 and -85 dbm in WiFi and microwave interference situation, respectively. Therefore, the results confirm that RSSI can be used as HI indicator, because it can identify the existence of heterogeneous interference successfully.

TABLE I. EXPERIMENT PARAMETERS

Settings	**Parameters**		
	WSN	***WiFi***	***Microwave***
Protocol	802.15.4	802.11b	-
Transmission Power	-	18 dbm	700W
Channel	22	11	-
Center Frequency	2460MHz	2462MHz	2450MHz
Bandwidth	5MHz	20MHz	-
Distance	-	1m	1m
Measuring Interval	500 ms		

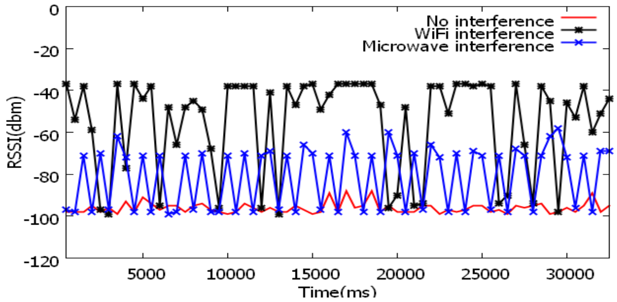


Fig. 2. HI measurement results with RSSI.

B. HI Estimation Model

First, we define variables as follows [7]:

- T_s is the sampling interval.
- V_{rssi} is a vector of a set of RSSI instantaneous value collected in T_s.
- $|V_{rssi}|$ is the number of RSSI instantaneous value collected in T_s.
- $\overline{V}_{rssi}$ is the average value of RSSI in T_s.

$$\overline{V}_{rssi} = \sum_{i=1}^{|V_{rssi}|} \frac{V_{rssi}(i)}{|V_{rssi}|} \tag{1}$$

- $HI_{threshold}$ is the interference threshold, its default value is -90dbm.
- V_{active} is 0/1 vector. If $V_{rssi} > HI_{threshold}$, $V_{active}(i) = 1$; else, $V_{active}(i) = 0$.
- $|V_{active}|$ is the number of V_{active} vector.

Then, we define HI Estimation Model as follows:

Definition 1. HI Value (P)

$$\begin{cases} \overline{V}_{rssi} \geq HI_{threshold}, P = \overline{V}_{rssi} - HI_{threshold} \\ \overline{V}_{rssi} < HI_{threshold}, P = 0 \end{cases} \tag{2}$$

Definition 2. Active Ratio (A)

$$A = \sum_{i=1}^{|V_{active}|} \frac{V_{active}(i)}{|V_{active}|} \tag{3}$$

Definition 3. HI Intensity (I)

$$I = P \cdot A \tag{4}$$

HI Estimation Model judges whether the interference exists and calculates the intensity with the average value of RSSI obtained by monitoring window.

IV. POTENTIAL FIELDS DEISIGN

In this section, we will describe how to construct the routing potential fields using depth and HI intensity, respectively, and then how to integrate them together to make dynamic routing decision.

A. Terminology

Neighbor. The neighbor of node i is all the nodes in the radio coverage disk of node i except for i itself, denoted by $N_e(i)$.

Depth. The depth of node i represents the distance from node i to the sink. Thus, if the shortest path algorithm chooses the radio hops as its routing metric, the depth of node i will actually become the shortest path length, denoted by $D(i)$.

HI intensity. The HI intensity of node i is the value of heterogeneous interference strength which node i is suffered from. It is defined by HI estimation model, denoted by $HI(i)$.

Potential energy. The potential energy of node i is the position of node i in the potential field, denoted by $PE(i)$. Correspondingly, depth potential energy, HI intensity potential energy and hybrid potential energy is denoted by $PE^d(i)$, $PE^{hi}(i)$ and $PE^h(i)$, respectively.

Potential field force. The potential field force from node i to node j is acting on the packet p at node i based on the potential difference between node i and node j, denoted by $F_{i\to j}$. Correspondingly, depth potential field force, HI intensity potential field force and hybrid potential field force is denoted by $F^d_{i\to j}$, $F^{hi}_{i\to j}$ and $F^h_{i\to j}$, respectively.

B. Depth Potential Field

As described above, depth potential field provides the basic routing function. Thus, to make packet p at node m flow directly toward the sink, we define the depth potential energy at node m as

$$PE^d(m) = D(m) \tag{5}$$

In addition, we define the depth field force from node m to node n, $n \in N_e(m)$ as

$$F^d_{m\to n} = PE^d(m) - PE^d(n) \tag{6}$$

In HIADR scheme, the default depth of sink node is 0, and the depth of other nodes is initialized to maximum in the beginning. The sink first sends update message, and the other nodes obtain their own depth by adding 1 on the depth value in the update message from their neighbor one hop away. When network topology changes, HIADR will recalculate the depth by adding 1 to the minimum effective depth value remained in the routing table.

C. HI Intensity Field

HI intensity potential field makes the algorithm interference aware. Hence, in order to avoid a hotspot which is identified by HI intensity, packet p at node m must move to node n, $n \in N_e(m)$ with lower HI intensity potential energy. Thus, we define the HI intensity potential energy at node m as

$$PE^{hi}(m) = HI(m) \tag{7}$$

Then, we define the HI intensity field force from node m to node n, $n \in N_e(m)$ as follows:

$$F^{hi}_{m\to n} = PE^{hi}(m) - PE^{hi}(n) \tag{8}$$

Driven by this potential field, packets will always be forwarded toward the weak or no interference areas, bypassing the interference affecting spots.

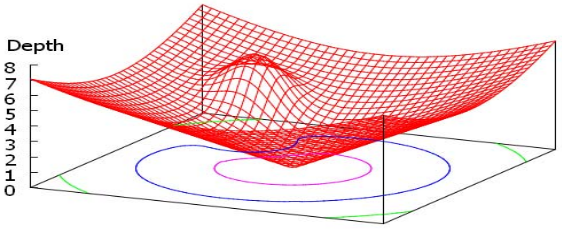


Fig. 3. Hybrid potential field example.

D. Hybrid Potential Field

We have defined two different potential fields. How the HI intensity field makes the routing algorithm interference aware is the main attributes of HIADR scheme. Hence, the two independent potential fields need to be superposed together properly to impose the impact on routing decision. Linear and nonlinear are two common combination patterns. For simplicity and tractability, we linearly combine the two potential fields as follows:

$$PE^h(m) = (1-\alpha)PE^d(m) + \alpha PE^{hi}(m) \tag{9}$$

The adjustable α independently controls the degree of influence of two fields on routing decision, $0 \le \alpha \le 1$. Then, the combined force from node m to node n, $n \in N_e(m)$ is

$$F^h_{m\to n} = PE^h(m) - PE^h(n) \tag{10}$$

This equation can be rewritten as

$$F^h_{m\to n} = (1-\alpha)F^d_{m\to n} + \alpha F^i_{m\to n} \tag{11}$$

Fig.3 depicts an example of the hybrid potential field. The heterogeneous interference only appears on a small part of nodes, where the potential field bulges.

V. DISCUSSION

In this section, we will discuss some auxiliary mechanisms including solution for "basin" problem and parent selection to ensure algorithm effective.

A. Solution for "Basin" Problem

Heterogeneous interference may produce interference within a period of time. Therefore, in some local areas, the potential energy of all neighbor nodes may be continuously high, which will make current node have no parent to route during the time. This is an interesting phenomenon in the HI intensity potential field, which can be viewed as a "basin" illustrated in Fig.4.

Current node is on the bottom, packets routing by it can't be forwarded during the time. Directional forwarding algorithm is the simplest way to solve this problem. With this method, the bottom node will forward the packet to the neighbor that potential energy is minimum. Although directional forwarding is enable to ensure routing is not dead, but subsequent packets will flow into "basin" along the direction of the minimum potential energy once again.

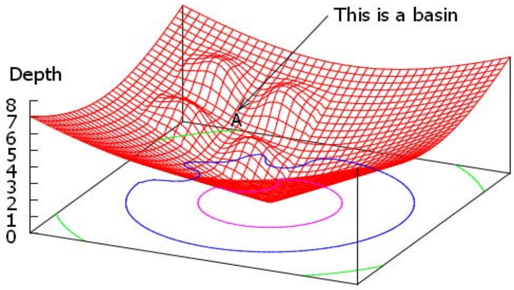


Fig. 4. The "basin" caused by HI potential field.

Based on the above considerations, we introduce an incremental potential energy into directional forwarding algorithm illustrated in Fig.5. If the current node is in the bottom of "basin", we raise its potential energy above the minimum potential energy neighbor, then route packets with the existence rules.

If A is the bottom node, A′ is the position of A after potential energy increases, and B is the minimum potential energy neighbor node, then, the specific algorithm is shown as follows:

$$PE(A') = PE(A) + \Delta PE \tag{12}$$

$$\Delta PE = PE(B) - PE(A) + \varepsilon \tag{13}$$

$\mathrm{PE}(\mathrm{A}')$, $\mathrm{PE}(\mathrm{A})$, $\mathrm{PE}(\mathrm{B})$ is the potential energy of A′, A, B respectively. $\Delta\mathrm{PE}$ is the incremental potential energy. ε is the adjustable parameter, $\varepsilon > 0$.

The depth of parent node must be lower or same with the current node, which guarantees the routing flow into the sink and have more opportunities to bypass the interference affecting nodes. As considering on the "basin", we don't need the higher depth nodes to be the parent, because it may cause another problem which can be called "reflux concussion". In that situation, the potential energy of current node and parent node increases alternately. The two nodes become the parent alternately at the same time. Therefore, packets could only flow between them, forming a dead loop.

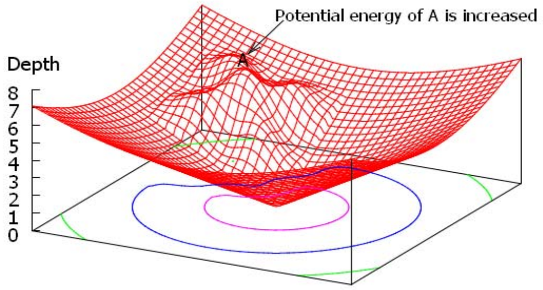


Fig. 5. Increment of potential field example.

B. *Parent Selection*

HIADR uses the steepest gradient method to choose the parent. Note that, in a lightly heterogeneous interference affecting area or a lightly heterogeneous interference affecting period, the steepest gradient rule will choose the shortest paths. Otherwise, it will dynamically choose multiple detour paths, since the HI intensity is dynamically changing. More precisely, a set of selection rules must be complied with as follows:

- **Rule 1:** $\mathbf{Depth}_{\text{parent}} \leq \mathbf{Depth}_{\text{current}}$.
- **Rule 2: Maximum Potential Force Neighbor.**
- **Rule 3: Minimum HI Intensity Neighbor.**
- **Rule 4: Random.**

If there are more than one neighbor which has the same depth, HIADR will choose the next hop node according to maximum potential force and minimum HI intensity neighbors in turn. After doing that, if HIADR still cannot determine the candidate parent, it will choose one randomly.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of HIADR using experiments conducted on the MICAZ platform built in TinyOS-2.x. The benchmark protocol is CTP, which employs hops from the sink and quality of radio links to find the next hop. 4BITLE is used by CTP at the local node to identify the link quality.

A. *Performace Metrics*

To make a comprehensive performance evaluation, we first define three quantitative metrics.

1) PRR (Packet Reception Rate). It is defined as

$$PRR = \frac{Number\ of\ packets\ received}{Number\ of\ packets\ injected}$$

PRR is the appropriate metric that reflects the fidelity of data application requirement because it will decline severely if the routing path is affected by the interference.

2) APL (Average Path Length). It is defined as

$$APL = \frac{Total\ number\ of\ hops\ by\ all\ packets}{Number\ of\ packets\ injected}$$

APL is the appropriate metric that reflects the parent chosen and topology change frequency of routing algorithm because it will increase if the routing path is affected by the interference. Lower the APL, higher the algorithm efficiency.

3) FPA (Forwarding Packets Amount). It is defined as number of packets forwarded per node. FPA is the appropriate metric that reflects the ability of routing algorithm to avoid interference and choose multipath because it will decrease if the node is affected by the interference and increase if interference become weak or no existence.

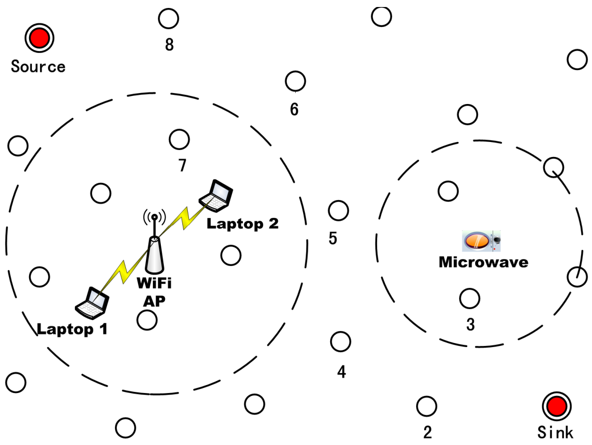


Fig. 6. Experiment scene.

B. *Experiment Setup*

Fig.6 shows a randomly deployed multi-hop network including 23 nodes spreading over a 10m × 5m square. Node 1 is the sink. Node 9 is the source. The radio wave range is 1m. We choose a microwave (MW), a WiFi AP and 2 laptops as interference sources. The detailed deployment configuration is summarized in Table II. The specific algorithm parameters are set in Table III. The occurrence of the interference events are described in Table IV.

TABLE II. EXPERIMENT CONFIGURATION

Settings	**Parameters**		
	WSN	***WiFi***	***Microwave***
Protocol	802.15.4	802.11b	-
Transmission Power	-20dbm	low power	700W
Channel	20	10	-
Center Frequency	2450MHz	2455MHz	2450MHz
Bandwidth	5MHz	20MHz	-
Interference Range	-	0~2m	0~1m
File Transmission Rate	-	200Kbps	-
Dot Pitch	1m		

TABLE III. ALGORITHM CONFIGURATION

Settings	**Parameters**	
	HIADR	***CTP***
Application Type	Event-driven	Event-driven
Data Packet Size	57 Byte	24 Byte
Update Packet Size	19 Byte	5 Byte
Interference Updating Threshold	5dbm	-
RSSI Sampling Interval	200ms	-
RSSI Processing Interval	1s	-
PE Caculation Interval	2s	-
α	0.7	-
Sending Interval	3s	
Measuring Interval	300s	

TABLE IV. EVENTS DISCRIPTION

	Event1	***Event2***	***Event3***	***Event4***	***Event5***
WiFi	OFF	ON	OFF	ON	OFF
Microwave	OFF	OFF	ON	ON	OFF
Starting Time	0s	300s	900s	1500s	2100s
Ending Time	300s	900s	1500s	2100s	2400s

C. Comparative Analysis

1) Packet Reception Rate (PRR). Fig.7 shows the PRR value of different schemes, which is an average over periods of 300s. Obviously, there are a lot of packets, which are likely dropped by CTP, eventually reach the sink by HIADR. Thus, HIADR successfully avoids the interference and improves the overall performance.

2) Average Path Length (APL). Fig.8 presents the average path length. The reason that HIADR has longer APL is packets are scattered to multiple paths and most packets travel for more hops before reaching the sink. This cost needs to be paid for achieving high throughput. Compared with the shortest path routing algorithm and CTP, HIADR makes a detour, which implies that the end-to-end delay increases.

3) Forwarding Packets Amount (FPA). Intuitively, Fig.9 exhibits the distribution of packets amount on every forwarding nodes over the time. Obviously, The forwarding packets amount in interference affecting areas of HIADR is less than CTP. This means HIADR spreads packets over the network and utilize sufficient node resources. Although CTP tries to avoid interference but it doesn't process properly. Link quality estimation in CTP is not comprehensive enough to reflect HI intensity.

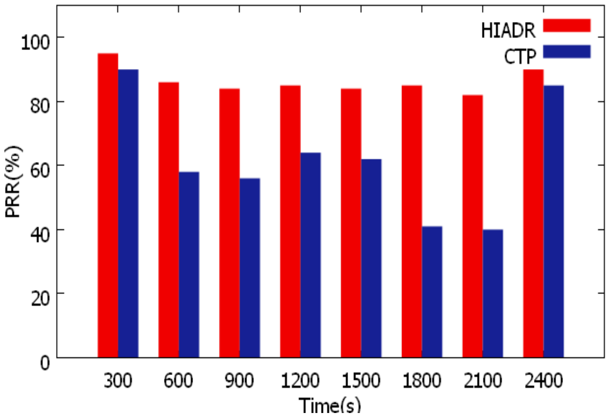


Fig. 7. PRR of transmission over the time.

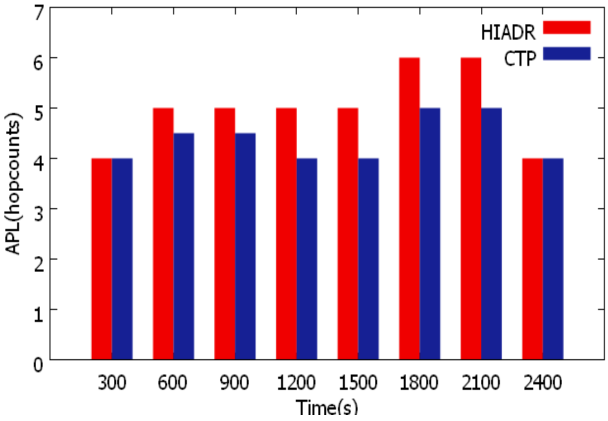
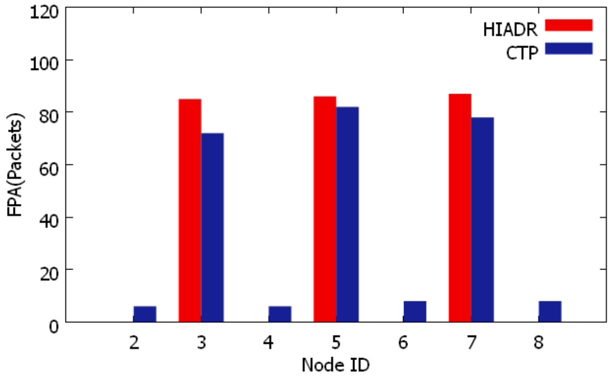
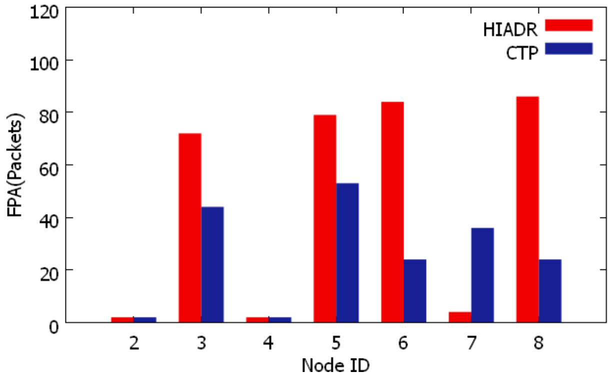


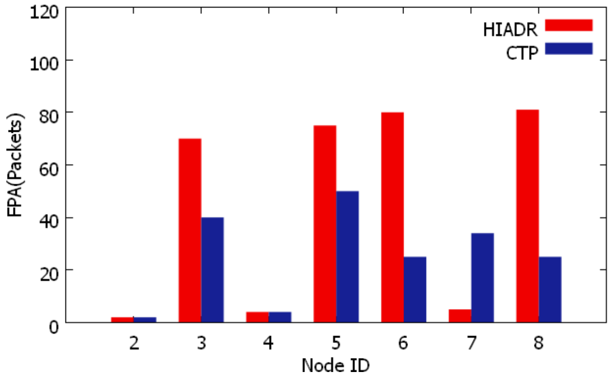
Fig. 8. APL of transmission over the time.



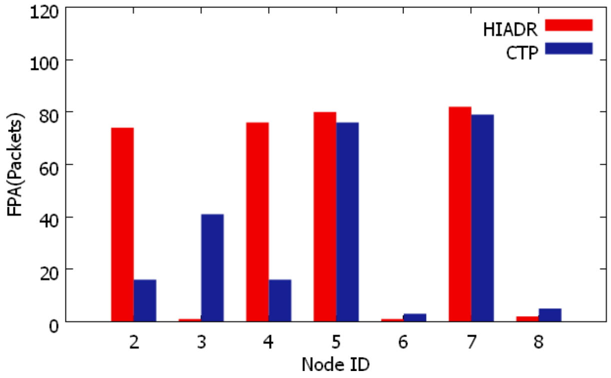
(a) 0~300s



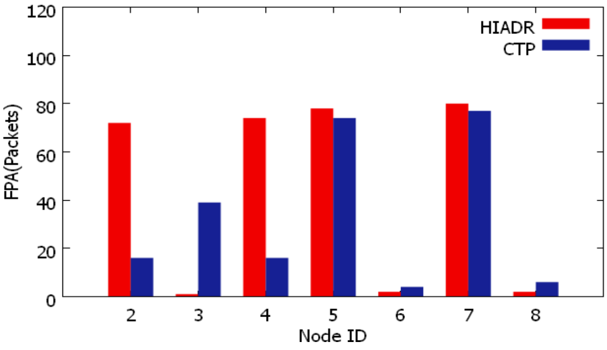
(b) 300~600s



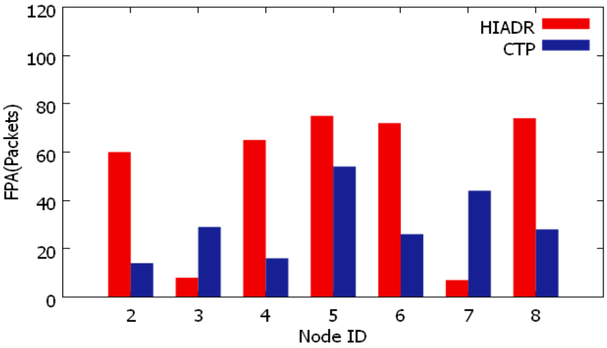
(c) 600~900s



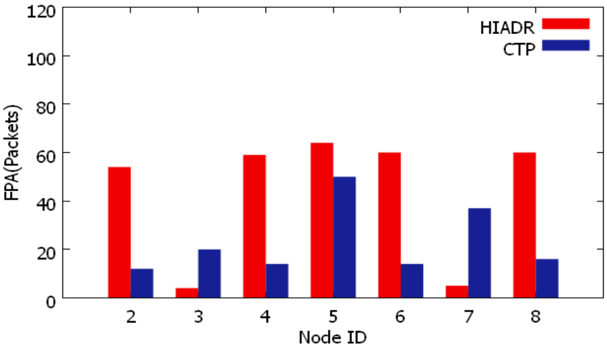
(d) 900~1200s



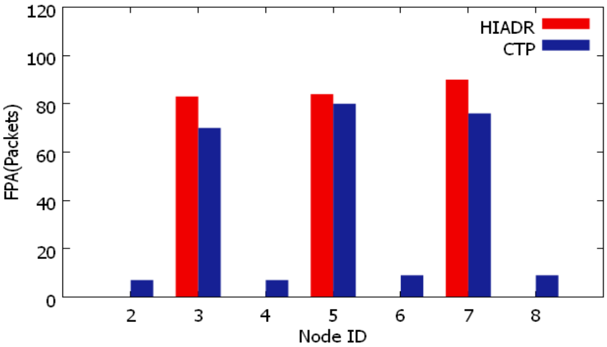
(e) 1200~1500s



(f) 1500~1800s



(g) 1800~2100s



(h) 2100~2400s

Fig. 9. Distribution of packets on forwarding nodes over the time.

VII. CONCLUSION AND FUTRUE WORK

WSN is different from other wireless systems, such as Wireless LAN and Bluetooth, which can't turn on more resources themselves to avoid interference. In this work, we follow the philosophy of dynamic capacity planning to deal with the interference problem in WSN through a smarter way. By carefully examining the special characteristics of WSN, we propose a potential-based HI-aware dynamic routing algorithm, called HIADR. The key idea underlying our algorithm is to define a hybrid scalar potential field, which contains a depth field and a HI intensity field. The depth field provides the basic routing backbone which routes the packets directly to the sink along the shortest path. The HI intensity field makes interference aware. When the interference appears, the affected packets are dynamically rerouted to multiple paths consisting of weak or no interference affecting nodes. Therefore, the HIADR scheme can effectively avoid interference through bypassing the hot spots, and improve the overall performance.

Other different types of interference are worthwhile to investigate in the future, like isomorphic interference. Moreover, an open framework is needed to adapt to the diversity. We believe that a general framework provided by the potential-based routing paradigm could be extended to deal with complex interference with additional mechanisms for performance enhancement. These may be possible subjects of future work in this direction.

ACKNOWLEDGMENT

The authors gratefully acknowledge the anonymous reviewers for their constructive comments. This work is supported in part by the National Grand Fundamental Research Program of China (973) under Grant No.2009CB320504, 2012CB315803, and the National Natural Science Foundation of China (NSFC) under Grant No.61225011.

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