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Turning heterogeneity into an advantage in wireless ad-hoc network routing

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A B S T R A C T
With increasing diversity of wireless devices, heterogeneity in transmission power is expected to commonly appear in ad-hoc networks. We observe that the existence of high-power nodes may adversely affect the performance of traditional ad-hoc routing pro- tocols such as AODV and DSR. A simple fallback strategy (i.e. high-power nodes transmit- ting at low-power levels) may solve the problem, but may not be efficient since it ignores the extra capability of high-power nodes. In this work, we view different levels of power heterogeneity as different tiers in the network. We propose a Tier-based RoutIng Frame- work (TRIF) which tackles the asymmetric link problem while taking advantage of long- range transmissions by high-power nodes. In contrast to other approaches that require periodic beaconing, TRIF allows the source to discover paths with symmetric links on the fly. By avoiding dependence on periodic beaconing, TRIF requires low overhead and is robust to network dynamics. TRIF does not require changes to the MAC layer, and can be utilized by any wireless devices that support dynamic transmission power control. TRIF can be leveraged to compute the optimal transmission power level over each link in order to reduce interference. Our simulation results show that TRIF can significantly outperform traditional ad-hoc routing protocols in heterogeneous environments.
Keywords: *Heterogeneous networks Asymmetric link detection Tiered-based routing*

I. INTRODUCTION

Recent studies of deployed WiFi networks have shown that 802.11 NICs (Network Interface Cards) from a wide range of vendors are in operation across various cities [1,2]. Among other characteristics, the wireless cards from different vendors often differ significantly in terms of their transmission power levels. The existing variation in power levels in deployed wireless cards strongly indicates that link asymmetry due to heterogeneity in power levels will occur commonly in ad-hoc networks. Although other types of heterogeneity such as computation power, storage space, and battery resource may occur across the nodes, in this paper we focus on link heterogeneity caused by var- iation in transmission power levels. In this context, we use the term heterogeneous nodes to refer to the nodes with higher transmission power.

In Fig. 1a, we construct a simple static topology in the well-known network simulator ns2 [3] where node 0 needs to send data to node 4. Each node in the network except node 1 has a transmission range of 30 m. We assume that node 1 is a heterogeneous node and study its impact on the routing process. We gradually increase the transmission range of node 1 from 30 m to 70 m. Fig. 1b illustrates the packet delivery fraction (PDF) by the transmission range of node 1 for two well-known ad-hoc routing protocols, AODV

[4] and DSR [5]. We observed that the PDF of both routing protocols degrades seriously when the transmission range of node 1 exceeds 60 m. We fix node 1’s transmission range at 60 m and consider a larger topology of 4 5 nodes (see Fig. 1c). In this scenario, both protocols were able to find a stable route from node 1 to node 4 with a PDF of 100%. However, the route discovery process takes over 10 s for AODV and about 20 s for DSR as compared to less than

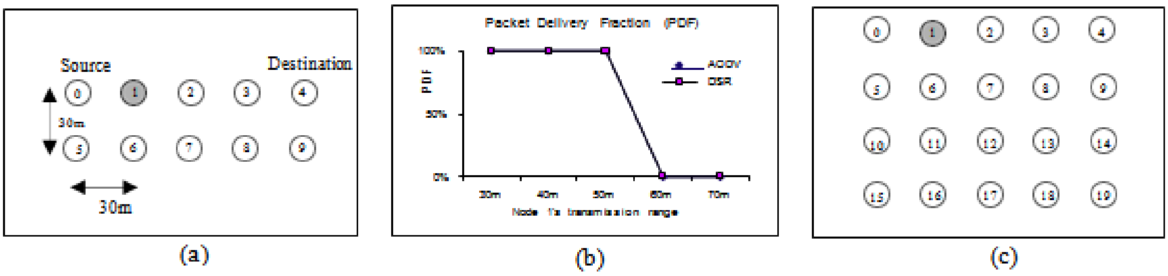

Fig. 1. Affects of heterogeneous nodes to a network's performance. Node 1 is a heterogeneous node. Other nodes have a 30 m transmission range.

s when the network is homogeneous. For a random net- work, the existence of 15 heterogeneous nodes in a net- work of 100 nodes may reduce the throughput by up to 50% as we will show later in the Performance Evaluation Section.

The reason behind the serious performance degradation is the asymmetry of some links caused by the long trans- mission range of node 1 (Fig. 1a). During the route discov- ery process, the selected path from the source (node 0) to the destination (node 4) contains an asymmetric link be- tween node 1 and node 3. When the route reply was sent back from the destination to the source, it could not get to the source because node 1 is out of node 3's transmis- sion range. A simple solution for this problem is to use fallback technique: node 1 only uses the lowest transmis- sion power level like other nodes. This makes all the nodes in the network homogeneous and avoids all problems caused by asymmetric links. However, the downside of this approach is it ignores completely the extra capabilities of the heterogeneous nodes. In some situations, having all nodes using the lowest transmission level may cause some parts of the network to be separated. In other cases, it can lead to unnecessarily long paths.
There have been two different paradigms in using the extra capabilities of heterogeneous nodes in wireless ad- hoc network routing. The first paradigm tries to avoid the use of long-range links provided by heterogeneous nodes whenever possible. It argues that in addition to creating the problem of asymmetric links, using the long-range links may increase energy consumption and reduce overall network throughput (due to the fact that energy consump- tion and interference range are proportional to the square of the transmission power). As a result, solutions under this paradigm attempt to use low-power links whenever possible (Fig. 2a). High-power links are only used when the destination cannot be reached with low-power links. Solutions in this category include [6,7]. In COMPOW [6], for instance, the authors determine the common minimum transmission power level for all nodes so that the network is still connected. All nodes use this common power level in order to avoid asymmetric links in the network.
On the other hand, the second routing paradigm [8–15] tries to take advantage of long-range links provided by the high-power nodes (Fig. 2b). Solutions in this category ar- gue that by using long-range links, the number of hops on a path can be reduced. This reduces transmission delay and makes the paths less susceptible to negative hop-by- hop instabilities, such as node movement, node malfunc- tioning, or channel fading effects. In terms of overall throughput, using high-power links is only disadvanta- geous if the network operates near its capacity. Below that, the effects are often small and can be tolerated by the advantages in terms of reliability and delay.

In the scope of this work, we do not compare the above two route selection paradigms because each of them is suit- able for a specific application domain. This paper follows the second paradigm, and is aimed to improve routing for net- works where the second paradigm applies. In order to de- tect valid routes, existing solutions either build a shortest path to the destination regardless of the symmetry of the

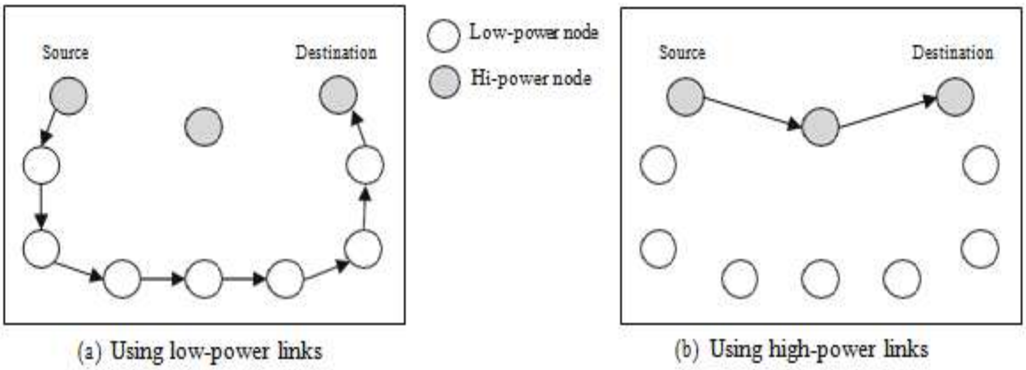

Fig. 2. Different route selection paradigms.

links, or use only symmetric links on the path. Several shortcomings of these solutions are: First, they require nodes to pre-collect information about heterogeneous nodes and asymmetric links, and update this information using periodic beaconing. Hence, they are not suitable to ad-hoc situations where nodes can frequently move, or where beaconing should not be used to conserve energy (e.g. sensor networks). Second, many solutions do not con- form to 802.11 standards, or require significant modifica- tions to MAC layer. This makes them not suited for millions of 802.11-based wireless devices in operation to- day. Finally, these solutions do not provide a mechanism to dynamically compute the optimal transmission power level over each link, which may lead to lower throughput (due to more interference) and higher energy consumption. In this paper, we view different levels of power hetero- geneity as different tiers in the network. We propose a Tier-based RoutIng Framework (TRIF) which can both tackle the asymmetric link problem and ensure the heter- ogeneous nodes are efficiently used in the routing process.
The salient features of TRIF include:
TRIF allows the source to find a symmetric path to the destination on the fly, i.e. it does not require nodes to pre-collect and update topology information.
TRIF can compute the optimal transmission power over each link in order to reduce interference and save energy.
TRIF is highly deployable as it does not require changes at MAC layer. Any device that supports dynamic trans- mission power control can take advantage of TRIF.

TRIF relies on the principle that if a receiver receives a sequence of RREQ packets from a sender, each with a differ- ent transmission power level, it will be able to infer about the symmetry of the link and the optimal transmission power level between the two nodes. Our implementation and evaluation of TRIF in the well-known network simula- tor ns2 [3] show that TRIF can significantly outperform tra- ditional ad-hoc routing protocols in heterogeneous environments.
The rest of this paper is organized as follows. Section 2 summarizes the related work in the area, and Section 3 introduces the network model. Section 4 presents our pro- posed routing framework (TRIF) while Section 5 theoreti- cally analyzes and compares TRIF with a traditional asymmetry-unaware routing protocol. We perform simu- lations to evaluate the performance of our proposed frame- work in Section 6, and discuss possible extensions of TRIF in Section 7. Finally, we draw our conclusions in Section 8.

II. RELATED WORK

As mentioned in Section 1, two different routing para- digms exist in power-heterogeneous environments. The first paradigm [6,7] tries to avoid the use of long-range links while the second routing paradigm [8–15] tries to make use of the extra capabilities of the high-power nodes whenever possible. Since each routing paradigm has its own applica- tion domain, comparing them is not possible. This paper belongs to the second routing paradigm, and therefore, we only discuss related solutions under this paradigm.

Under the second routing paradigm, using tunneling to hide the unidirectional nature of the links is the common approach shared by many of the solutions [8–15]. When the sender is out of the receiver's range, a multi-hop tunnel from the receiver to the sender is formed using the infor- mation gathered by the routing protocol. The path between the source and the destination is the shortest path between the 2 nodes and may include unidirectional links. However, many of these solutions [11–15] only discuss the problem at the routing layer. They ignore MAC layer interaction, and are not applicable in real deployment. For instance, under 802.11, any two nodes exchanging data also need to ex- change a set of control packets, such as RTS, CTS and ACK. A path like 1–2–4–5 in Fig. 3, which is considered as a legitimate and desired one in the schemes above, is not a valid path under 802.11 since node 2 cannot receive CTS and ACK packets from node 4. The other solutions in this category [25,8,9] requires significant modifications at MAC layer to forward CTS/ACK packets within a number of hops (as opposed to no forwarding in standard 802.11) in order to ensure that the sender can listen to the recei- ver's CTS and ACK packets. Since this technique is not sup- ported by the standard 802.11, the protocol is not applicable to the millions of 802.11-based wireless devices in operation today. Besides that, the multi-hop forwarding of control packets also significantly increases the number of packets transmitted at MAC layer. In [26], the authors consider the problem of multicast routing in a network with unidirectional links. Since traffic in the network is broadcast, the requirement of exchanging control packets (i.e. CTS/ACK) can be relaxed and unidirectional links can be utilized to improve performance.

A different approach to solve the asymmetric link prob- lem is to use only symmetric links in the paths, as men- tioned in [16–18,24]. To detect the symmetry of the links, each node embeds a list of all nodes that it can hear from in its beacons (i.e. Hello messages). Based on this information, each node will be able to create a list of sym- metric links (from itself) and use only these links in the routing process. The downside of this approach is nodes have to waste energy for sending out periodic beacons even when they do not have any data to send. Besides that, determining the beacon rate in order to maintain topology

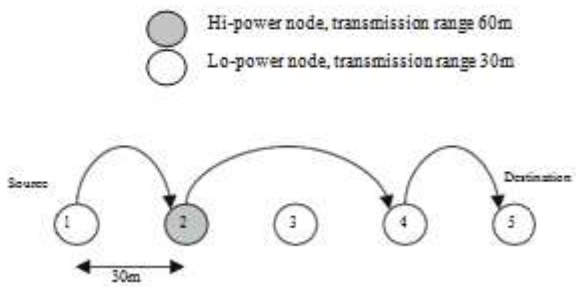

Fig. 3. Under 802.11, the path 1–2–4–5 is not legitimate because node 4's CTS and ACK can not be heard by node 2.

information in a dynamic environment (i.e. with node movement) is also not a trivial problem.
In [23], the authors have proposed a solution to deter- mine the link asymmetry by embedding extra information on the packet header, including transmission power, noise level, received power threshold and minimum signal-to- noise ratio. Upon receiving a routing packet, the receiving node uses the embedded information to determine it is capable of reaching the sender with its maximum power. The challenge of this solution is the embedded parameters may not be easy to measure, and may not be standardized across different hardware vendors. Our solution takes a similar approach. Yet, we minimize any discrepancies in wireless device parameters by using a simple feedback mechanism. The only extra information embedded on the packet is the transmission power level of the packet. Our solution also allows nodes to optimize transmission power over each link, which efficiently reduce power consump- tion in data communication.
Besides these works, in [20–22], the authors look at the heterogeneous node problem in the wireless sensor net- work domain. Du et al. [20] and Sang et al. [22] proposes services and new metrics to measure link quality in net- work; and [21] evaluates the impact of number and place- ment of heterogeneous resources (in terms of energy, computation, and transmission range) on performance in network of different sizes and densities.

III. NETWORK MODEL AND ASSUMPTION

We consider a network with multiple nodes with differ- ent transmission power. We assume that the transmission range of a node is mostly dictated by its transmission power, which is the case of most common radio models (e.g. Free space, 2-ray ground). The transmission power can be discretized into different levels from 1 (lowest) to k (highest). We assume that nodes are aware of these lev- els. Even though there can be small variations in transmis- sion range caused by time and nodes' physical positions [18,19], we assume that these variations can be dealt with using a simple technique such as setting a reception threshold corresponding to each transmission power level. We view different levels of transmission power as differ- ent tiers in the network. Tier 1 of the network consists of nodes with minimum transmission capability while tiers
– 2 k may be composed of more powerful nodes. A tier-X node can transmit at any power level less than or equal to X. Throughout this paper, we also use the term tier for a packet to denote the

transmission power level at which the packet is transmitted. A tier-X packet is a packet trans- mitted at power level X from the sender.

IV. TRIF-A TIER-BASED ROUTING FRAMEWORK

TRIF is our proposed framework for handling power- heterogeneous networks. It can be incorporated to any RREQ (Route Request)/RREP (Route Reply)-based ad-hoc routing protocols. TRIF relies on the principle that if a recei- ver receives a sequence of RREQ packets from a sender, each with a different tier (i.e. transmission power level),

it will be able to determine the symmetry of the link and the optimal transmission power level between the two nodes. TRIF allows the source to find a symmetric path to the destination on the fly. It does not require nodes to pre-collect information about heterogeneous nodes and asymmetric links, and to periodically update this informa- tion. In detail, each intermediate sender and the receiver do as follows:

Sender side: When a sender wants to propagate a RREQ packet, it transmits the RREQ packet at different power levels, from 1 to its own tier (i.e. the sender's tier). These RREQ packets are sent in the descending order of power level. When a node sends out a RREQ packet, it tags the packet with the packet tier (i.e. the transmission power level at which the packet is sent).

Receiver side: When a node receives a RREQ packet, it only processes the RREQ packet if the packet's tier is less than or equal to its own tier (i.e. the receiver's tier). If not, the packet will be dropped. The intuition behind this is:

(i) If the link is bi-directional, a RREQ packet with a lower tier will arrive later since the sender sends out multiple RREQs at different tiers; and
(ii) If the link is unidirectional (only the sender can reach the receiver), it should not be considered for the reverse path.

We illustrate the route discovery process in Fig. 4: Source A (tier 1) broadcasts a single RREQ packet look- ing for destination E. Node B (tier 2) relays this packet with two RREQ packets, one of tier 2 and the other of tier 1. Node C (tier 3) continues this process with 3 RREQ packets, one of each tier from 3 down to 1. The tier-1 packet from C can not get to node D due to the long distance between the 2 nodes, so D only receives 2 RREQs from C (assuming the tier-2 packet from B cannot get to D). D drops the tier-3 RREQ from C as this packet's tier is higher than D's own tier (2), and sends out 2 packets of tiers 2 and 1. Des- tination E (tier 1) receives the RREQ packets of tiers 3 and 2 from C and drops them since they have higher tier than E's own tier (1). E also drops the tier-2 RREQ packet from D with the same reason. Finally, E receives the tier-1 RREQ from D and replies with a RREP. The selected path is A–B–C–D–E. If the tier-2 packet from B can reach D, it can be seen that the path A–B–D–E will be selected.

Note that it is also possible to send the RREQ packets in the increasing order of tier number. In our scheme, we give priority to the high-tiered nodes since these nodes can 2 & 3 from node C

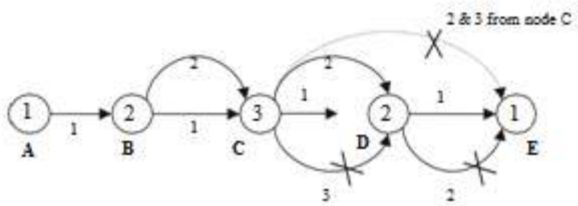

Fig. 4. RREQ transmission sequence. (Node tiers are numbers in the circles. Packet tiers are shown on the arrows).

generally reach the destination faster than other low- tiered nodes. Hence, the packets are sent out in the decreasing order of tier number so that the high-tiered nodes always have an advantage (in terms of time) over others in propagating the RREQ packets.

The pseudo code of this process is provided below.

```
Function SendRREQ(Packet RREQ)
{ // Create multiple RREQ with different tiers
   for (int tier=MyTier; tier>=1; tier–){
      // Create a new RREQ packet with same content
      new_req=RREQ.Copy();
      // Tag it with a proper tier
      new_req.Tier=tier;

Send new_req out to the airwave at a transmission power level corresponding to tier
}}
Function ReceiveRREQ(Packet RREQ)
{if (RREQ.Tier>MyTier)
   Drop the packet and return;

   // Similar to AODV: if a packet with this seq.# has not arrived, create a path to the originator of the RREQ packet

   If (! received a RREQ packet with this Sequence number before){
      Add a path to the RREQ's originator via its sender (i.e. RREQ.sender)
      That path.Tier=RREQPacket.Tier; // Setting the transmission power level
      That path.PreviousHop=RREQ.sender;
   } else{// receive a RREQ packet with same the sequence # before, update path tier if necessary
      path=find_path(RREQ.Sequence);
      if (path.PreviousHop==RREQPacket.sender) // A RREQ packet from the same sender as before
         path.Tier=min(path.Tier, RREQ.Tier); // Update path tier if necessary
      Return;
   }
   // Check if I am the destination if yes return the RREP
   If (RREQ.Destination==MyID){
      Create and send ROUTE REPLY message;
      Return;
   }
   // If I am not the destination, forward the RREQ packet
   RREQ.TTL–; // Reduce RREQ.TTL by 1;
   SendRREQ(RREQ);
}
```

The receipt of multiple RREQs, each at a different power level, helps a receiving node determine the optimal trans-

Table 1

Routing tables at different nodes.

Node	Destination	Next	hop	Link	tie r
A	E	B	1		
B	E	C	1		
B	A	A	1		
C	E	D	2		
C	A	B	1		
D	E	E	1		
D	A	C	2		
E	A	D	1		

mission power for the previous hop. For example, when C receives the first tier-2 RREQ from B, it knows that it can get to B with a link tier (i.e. transmission power level) of 2. Next, when the tier-1 RREQ from B arrives, it adjusts this link tier to 1, implying a transmission power level of 1 is sufficient for the link between B and C. When the RREP tra- verses from the destination to the source, this information is included on the RREP packet. Follows is the routing table for each node after the RREP gets back to A (see Table 1).

Since the only information embedded on the routing packet is the tier of the packet, the extra overhead per rout- ing packet is $\log_2 k$ bits where k is the number of tiers in the network. In reality, this only entails a very small cost in terms of communication speed and energy consumption. For instance, consider a network transmitting at 1 Mbps. If a routing packet has a header of 64 bytes (32 bytes of routing header, 20 bytes of IP header and 12 bytes of MAC header), the cost for sending an extra few bits of embedded tier information would be negligible for routing packets. Since data packets do not carry the embedded tier informa- tion, no extra costs are required for data transmission.

V. NETWORK PERFORMANCE ANALYSIS

In this section, we analyze the performances of a gener- ic ad-hoc routing protocol, modeled based on the well- known AODV [4] and DSR [5] routing protocols, and our proposed framework (TRIF) in the presence of heteroge- neous nodes. We divide this section into two parts: First, we calculate the probability of asymmetric links in the net- work; and second, we analyze the routing performance using this probability.

Asymmetric link probability

Asymmetric link probability is defined as the ratio of the number of asymmetric links to the total number of valid links. Links are directional and a link AB is considered as va- lid if node B can hear from node A (i.e. B is within A's trans- mission range). Note that in the routing process, only the valid links are selected and we cannot calculate the total number of valid links in the system as n (n is the num- ber of nodes in the system) because of this reason. The asymmetric link probability can be defined as:

2

PAsymmetric

Number of asymmetric links

¼ Number of asymmetric links þ Number of symmetric links

Let n and k be the total number of nodes and tiers in the system, respectively.

d , d ,..., d be the densities of the tier-1, tier-2.. .tier-k

Y_{mi} ¼ $d_1 \cdot S_1$ þ $d_2 \cdot S_2$ þ··· þ $d_m \cdot S_m$ þ $d_{m\text{þ}1} \cdot S_m$ þ··· þ $d_k \cdot S_k$; A_{mi} ¼ ðS_m — S_1Þ· d_1 þ ðS_m — S_2Þ· d_2 þ··· þðS_m — $S_{m—1}$Þ· $d_{m—1}$:

ð3Þ

1 2 k P P

nodes.

$R_1, R_2,..., R_k$ be the transmission ranges of the tier-1, tier-2.. .tier-k nodes.

And: Y_m ¼ S·dm Y_{mi} and A_m ¼ S·dm A_{mi}. i¼1 ¼ i¼1

The probability of asymmetric links is therefore:

P_k Am

m

S be the total area of the network.

$S_1, S_2,..., S_k$ be the areas of the circles whose radius are

R , R , , R , respectively.

PAsymmetric ¼ k

m¼1

m 1 P $_m$þ P
Y k
m¼1
A : ð4Þ
1 2 · · · k

Let us consider a tier-1 node N_{1i} (see Fig. 5a). Let Y_{1i} and A_{1i} be the number of symmetric and asymmetric links start- ing from N_{1i}.

A_{1i} is 0 because any node X reachable from N_{1i} will be able to reach N_{1i} (since its transmission range R(X) P R_1 because is N_{1i} a tier-1 node). Y_{1i} is the number of nodes lo- cated in the circle whose center is N_{1i} and radius is R_1. Hence:

Routing performance analysis

For this part, we ignore all the packet transmission fail- ure due to congestion and buffer overflow caused by high volume data transmission. We also ignore the effects of cache and route timeout in route discovery. We assume that as long as there is a valid path from the source to the destination, the data can be successfully transmitted. We assume that the network is large enough so that there

Y_{1i} ¼ $d_1 \cdot S_1$ þ $d_2 \cdot S_1$ þ · · · þ $d_k \cdot S_1$;
A_{1i} ¼ 0:
ð1Þ

can be multiple paths between any two nodes.

Asymmetry-unaware system

The number of symmetric and asymmetric links started from all tier-1 nodes is:

We consider the case of a generic asymmetry-unaware routing protocol. We assume that it behaves as follows,

8
≷ Y 1 ¼
> A
] S·d1
Y : 1 ¼
i¼1
] S·d1
A $_{1i}$ ¼
i¼1

1i ;

0 :

ð2Þ

which is true for both the case of AODV and DSR.

Any asymmetric link on a path will make the path • invalid.

- The source node after failing to detect a valid path to the

Now, consider a tier-2 node N_{2i} (see Fig. 5b).

Y_{2i} can be calculated using the same method as (1). However, A_{2i} is not zero anymore because any tier-1 node lying in the dotted area will cause the link from N_{2i} to that

destination will reinitiate the route discovery process

with a cost of N where N is the number of nodes in the system. The latency caused by each retry is T.

- The source node retries at most Y times.

node to be asymmetric. Hence:

Let p = pAsymmetric

be the probability of asymmetric links

-

Y2i ¼ d1 · S1 þ d2 · S2 þ d3 · S2 þ· · · þ dk · S2;
A2i ¼ ðS2 — S1Þ· d1:

The number of symmetric and asymmetric links started from all tier-2 nodes is

in the system, given in formula (4). We consider a path p between 2 nodes with length L. We assume that if p is an invalid path, the system will retry a different path with approximately the same length as p.

S·d2

S·d2

Packet delivery fraction. Since each hop has a prob-

Y2 ¼ X Y2i and A2 ¼ X A2i respectively:

ability of being asymmetric of p, the probability that each

i¼1

i¼1

hop is symmetric is (1 — p). The route is valid if all the links

In general, for tier-m node N_{mi}, we have:

are symmetric. Hence, the chance of successful route dis- covery for one attempt is:

wL 1 ¼ ð1—pÞL: ð5Þ

The probability that the routing protocol fails in the first (i — 1) attempts and succeeds at the i^{th} attempt is:

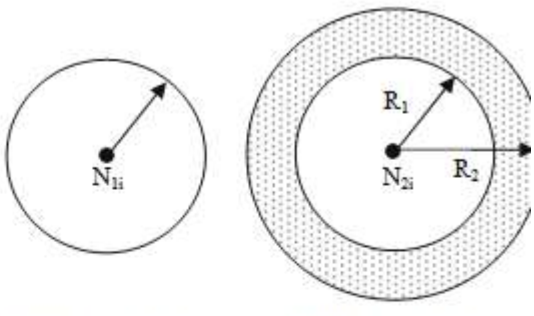

Fig. 5. Asymmetric and symmetric links of nodes of different tiers.

Hence, the probability that a symmetric route can be dis- covered in Y attempts is:

qL Y ¼ 1 — ð1 — wL 1þY ¼ 1 — ð1 — ð1 — pþLþY : ð7þ

Routing overhead (RO). The probability that the routing protocol succeeds at the ith attempt and the total routing overhead in this case are $w_{L,i}$ and i m n, respectively.

At the (Y 1)th attempt, the probability that the rout- ing protocol succeeds and the total routing overhead are

wL;1 ¼ 1; 8
≍ ZL;Y ¼ 1; >

$w_{L,Y-1}$ and (Y — 1)n respectively. If it does not succeed, the routing cost will be Ymn, regardless of the Yth attempt

i¼1 ;

≳ RO ¼

All nodes]

node >

· Tier

= n;

ð11Þ

is successful or not. Note that the probability for this to

RDT ¼ T:

(Note that the approximation for *RO* in formula 11 is only

happen is $1 - \sum_{Y-1} w_{L\,i}$.

Hence, the routing overhead (RO) for (a maximum of Y attempts) is:

valid when the number of homogeneous nodes dominates the number of heterogeneous nodes in the system).

RO ¼

Y—1

i¼1

wL;i m i m n þ 1 —

Y—1

i¼1

!

wL;i

m n m Y; ð8Þ

VI. PERFORMANCE EVALUATION

By replacing $w_{L,i}$ with (6) and expanding the geometric series in (8), we can further simplify RO to:

In this section, we perform simulations to compare the performance of our proposed framework TRIF with the two

RO ¼ nm

1 — ð1 — wL 1Þ^Y

wL;1

¼ nm

1—ð1—ð1—pÞ^LÞ^Y

ð1 — pÞ L

: ð9Þ

well-known traditional ad-hoc routing protocols, AODV and DSR, together with a BEACON-based approach (i.e. using periodic Hello messages to detect the symmetry of the links). The BEACON approach is implemented based on

Route discovery time (RDT). The route discovery time can be calculated in a similar manner as the routing overhead.

AODV with Hello message enabled (note that Hello is not enabled by default in AODV).

$$RDT = T\frac{1-(1-(1-p)^{L})^{Y}}{(1-p)^{L}}; \qquad (10)$$

6.1. Simulation environment

Simulations are performed using the well-known net-where T is the latency caused by each attempt. In case the route cannot be found, formula (10) gives us the period the source has to wait until it realizes that the destination is unreachable (after Y attempts).

Fig. 6a–c illustrate the trends of the asymmetric link probability, the successful route discovery probability and the total routing overhead for a system with 100 nodes spread out in an area of 200 200 m. The network has two tiers with transmission ranges of 30 m and 60 m, respec- tively. The number of retries (Y) is 3. As can be seen in these figures, the variables (i.e. successful route discovery rate, routing overhead and route discovery time) are sensi- tive to the number of heterogeneous nodes. This indicates that it is critical to have a solution that can deal with asym- metric links.

TRIF-based system

Since TRIF is aware of link asymmetry, it is able to find a symmetric path at the first attempt. The system through- put, routing overhead and route discovery time can be for- mulated as:

work simulator ns2 [3]. The simulation parameters are indicated in Table 2.

Table 2

Simulation parameters.

Simulator	Ns2
Simulation time	300s
MAC layer	802.11
Radio model	Lucent WaveLAN
Total number of nodes	100
Network size	200 m × 200 m
Number of data sources	5–25
Traffic type	CBR
Data rate	1 kB/s
Beacon (BEACON approach) interval	1–30 s
Number of tiers	2
Regular node transmission range	30 m
Heterogeneous node transmission range	60 m
Number of tier-2 nodes	0–15
Node movement speed	0–8 m/s
Pause time	10 s

Asymmetric link probability

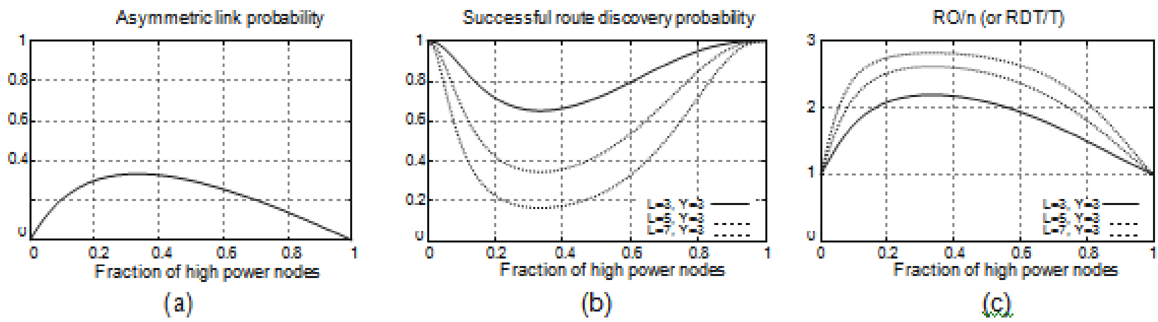

Fig. 6. Performance of an asymmetry-unaware system in the presence of heterogeneous nodes (L = path length, Y = number of retries).

Metrics

We evaluate the following metrics:

Packet delivery fraction (PDF): the ratio of the number of data packets delivered to the destinations to those gen- erated by the sources.
Normalized routing overhead: the number of routing packets transmitted per data packet delivered at the destination. Each hop-wise transmission of a routing packet is counted as one transmission. In the case of BEACON, Hello messages are also included in the routing overhead.
Average end-to-end delay: the average time it takes to deliver a data packet, including the route discovery time if the route to the destination is not available at the source.

Simulation results

Fig. 7 shows the performances of all protocols in a static environment. As we are interested in the routing aspect, we use low-rate traffic (2 packets/s) to ensure no packets are dropped at each node due to congestion. With BEACON, each node sends out a beacon every 10 s. As shown in Fig. 7a, while the performances of both AODV and DSR de- grade quickly when the number of high-power nodes in- creases, both TRIF and BEACON are able to maintain PDF at 100%. The reason for the degradation of AODV and DSR is because these two protocols can not handle asymmetric links whose existence is proportional to the number of high-power nodes. The normalized routing overhead of
AODV and DSR increases rapidly with the number of high-power nodes as shown in Fig. 7b due to two reasons: first, the total routing overhead increases sharply since these protocols need to restart the route discovery process multiple times, and second, the PDFs of these protocols plummet in these cases (see Fig. 7a). Compared to BEACON, TRIF has significantly lower overhead (less than 80% on average) because nodes do not need to send periodic Hello messages as in the case of BEACON.
In Fig. 8, we show the performances of all protocols in a dynamic environment where nodes move at a maximum speed of 3 m/s (note that the transmission range of tier-1 nodes is only 30 m). Under this condition, TRIF continues to outperform other protocols in all metrics. While this is obvious for the case of AODV and DSR, the degradation of BEACON (compared to TRIF) in terms of PDF can be ex- plained as follows: when nodes move (especially at high speed), neighborhood information obtained from periodic beacons may become outdated quickly and some of the paths selected by BEACON contain asymmetric links, adver- sly affecting the performance of the protocol. Figs. 9 and 10 also show the advantages of TRIF over the other protocols under different data loads and different node movement speeds. Both AODV and DSR do not perform well under these conditions. BEACON and TRIF experience similar behaviors. This is because we have implemented both of these protocols based on AODV, and both are aware of asymmetric links in the network.

Finally, we compare the performance of TRIF and BEA- CON under different beacon rates in Fig. 11. There are 10 high-power nodes and 15 active data sources. Nodes move at a maximum speed of 5 m/s. Energy consumption is 281 mW for both txPower and rxPower (these are the de-

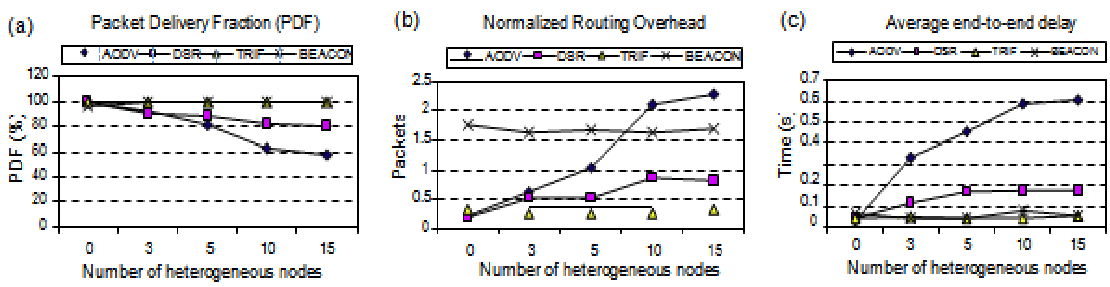

Fig. 7. Performance of TRIF in a static environment (5 data sources, data rate: 2 packets/s).

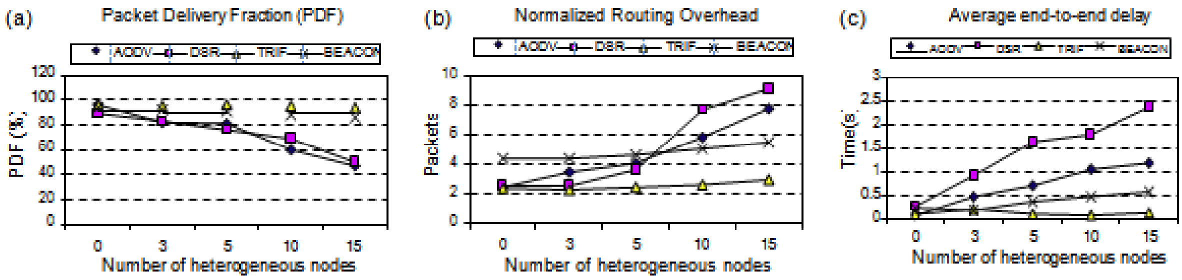

Fig. 8. Performance in of TRIF a dynamic environment (5 data sources, data rate: 2 packets/s, movement speed: 3 m/s).

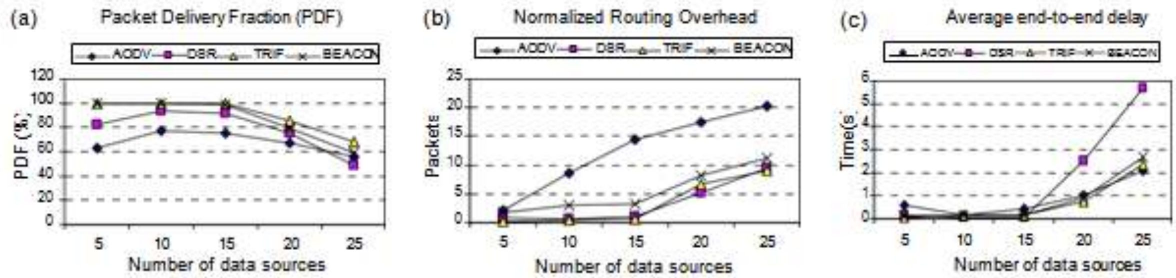

Fig. 9. Performance of TRIF under different data loads (Nodes are static, 10 heterogeneous nodes, data rate: 2 packets/s per data source).

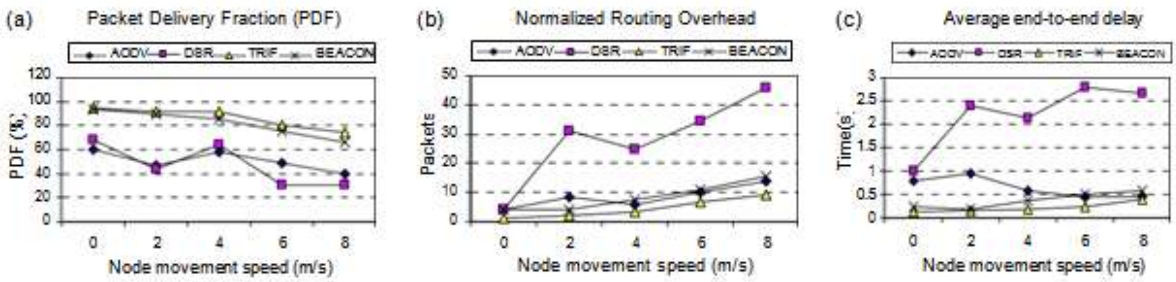

Fig. 10. Performance of TRIF under different node movement speeds (10 heterogeneous nodes, 10 data sources, data rate: 8 packets/s).

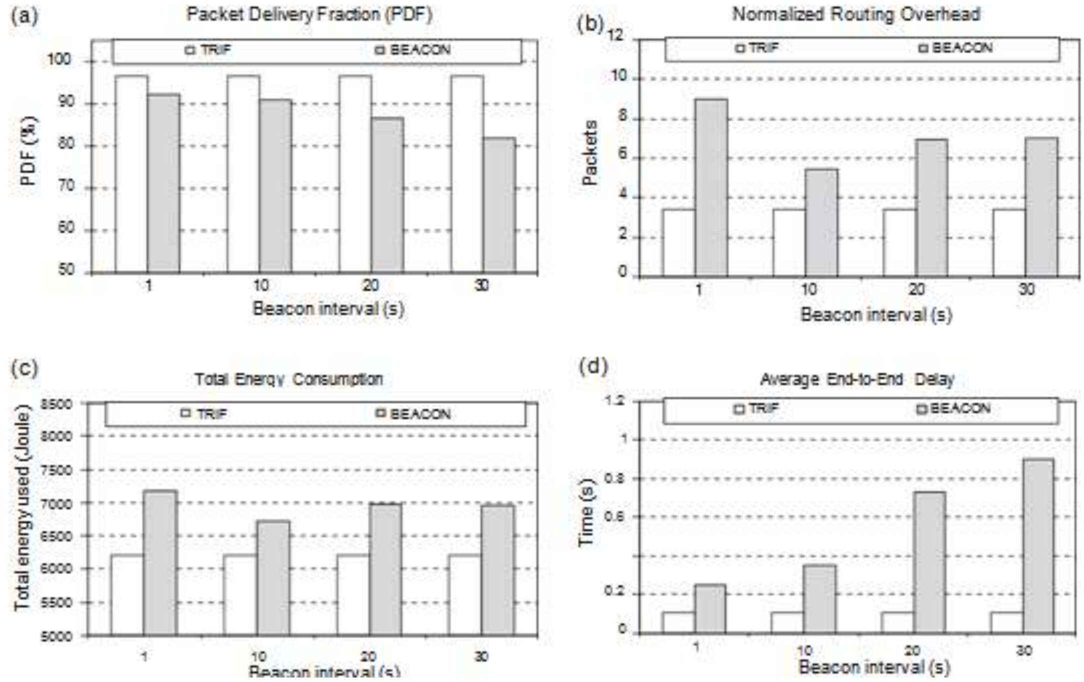

Fig. 11. Effects of beacon interval to the performance of BEACON (10 heterogeneous nodes, 15 data sources, node movement speed: 5 m/s, data rate: 2 pkts/s).

fault values in ns2). Movement energy is excluded in our calculation. With the BEACON approach, reducing the bea- con rate while lowering the normalized routing overhead decreases PDF and increases end-to-end delay. This is be- cause as the beacon interval increases, neighborhood infor- mation detected by the BEACON approach may become outdated quickly. Some of the paths detected actually con- tain asymetric links, reducing the throughput of the sys-tem. As can be seen in Fig. 11c, total energy consumption goes down when the beacon interval increases from 1 to 10, and goes up again when the beacon interval increases further. This can be explained by looking at the energy con- sumption for beacon transmission and packet transmission separately. As we increase beacon rate from 1 to 10, we actually reduce the energy for beacon transmission by 10 times, leading to a decrease in normalized routing overhead and total energy consumption. On increasing the beacon interval above this value (i.e. one beacon every 10 s), the energy saved by reducing beacon rate is outweighed by that for packet re-transmission and route recreation (note that PDF is quite low when the beacon interval is above 10 s as shown in Fig. 11a). Overall, energy consumption of TRIF is about 6–15% lower than that of BEACON. We note that in our simulation, nodes transmit data during most of the time. In actual applications where nodes send out data only in a fraction of their time, the energy saving of TRIF compared to BEACON can be signifi- cantly higher than that.

VII. DISCUSSIONS

In this section, we present some discussions on possible extensions of TRIF. We look at the following two aspects: how to provide load balancing routing in TRIF, and how to modify TRIF in order to favor low-power link routing.

Load balancing routing in TRIF

Under our approach, each node sends out a number of route request packets equal to its own tier. This makes the high-power nodes expend more energy than the low- power nodes because they have to send out more routing packets. Besides, the high-power nodes are also more likely to be included on any route. This may lead to the situation where most routes in the network concentrate on some high-power nodes, causing them to quickly run out of energy. To address this problem, nodes can follow an energy-adaptive policy as follows:

During each time period, each node only selects a ran- dom number of tiers on which it sends out route request packets. For instance, during the first hour, a node with tier 4 uses tiers 1 and 3. During the second hour, it uses tiers 2 and 4, etc. This process can be independently run at each node without any requirements about synchronization.

The number of route requests sent out is also propor- tional with its remaining energy. For instance, a node will forward RREQ at all power levels if it has abundant energy. Otherwise, it will only forward RREQ on a certain number of power levels.

These approaches help nodes exchange roles at run- time, and avoid situations where some nodes repeatedly serve as the core routing nodes for the network. However, we note that by doing so, the transmission power on some links may not be optimal. For instance, if node A can reach node B using a link tier 2, and if A uses only tiers 1 and 3, B may perceive that it has to send packets at tier 3 to reach A.

Low-power link-oriented routing

Currently, TRIF favors short paths with high-power links. In situations where low-power links are preferred (see Section 1), TRIF can be easily modified to adapt to this situ- ation by changing the order the RREQ packets are sent out. In this case, the RREQ packets are sent out in the increasing order of packet tier. In other words, line 3 of the pseudo code presented in Section 4 can be changed from:

```
3: for (int tier=MyTier; tier>=1; tier–){
...
to:
3: for (int tier=1; tier<=MyTier; tier++){
...
// Delay transmitting the packet
// proportionally to its tier
```

By sending out RREQ packets in increasing order of tier number, and by adding a small delay proportionally to the packet’s tier, we give priority (in terms of time) to the low- tiered packets so that they can reach the destination faster. Hence, paths with low-power links are more likely to be selected under this scheme.

VIII. CONCLUSION

In this paper, we have proposed a Tier-based Routing Framework (TRIF) to deal with the asymmetric link problem caused by transmission power heterogeneity in wireless ad-hoc networks. TRIF can both tackle the asym- metric link problem and ensure the powerful nodes are efficiently used in the routing process. TRIF is stateless and works on-the-fly. It can also compute the optimal transmission power level over each link in order to reduce interference and save energy. Our simulation results show that TRIF can significantly outperform traditional ad-hoc routing protocols in heterogeneous environments.

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