required neighbour or until the node reaches the maximum power. When considering COMPOW, it maintains a common power level, able to reach all nodes in the network. The performance of all these protocols is limited, considering the network dynamics. These approaches motivated us to develop a localized, asynchronous, neighbour-aware structure in wireless DTN that enables nodes to utilize their power fairly and efficiently.

1.1. Necessity of SH structure

Nodes able to form a tree structure are named as SH nodes (used for alternate routing). Once a node is identified as an SH node, it allows unidirectional data flow from leaf nodes (node attached with SH nodes or other than SH nodes/source/destination). This unidirectional flow is used to improve the network lifetime and reduce congestion. The necessity of power control is depicted in Fig. 1. Here nodes Nd1 and Nd3 need to send the packet to Nd2 and Nd4 respectively. Suppose maximum transmission power of each node is 25 mW. But here only 1 mW power is enough to transmit the packet from Nd1 and Nd3.

Thus it can save on battery power. Secondly, in the same figure Nd3 wants to send packet to Nd4 at 1 mW, Nd1 send at 1 mW to Nd2, then both transmissions are received successfully since sender nodes use minimum transmission power to reach destination. If Nd1 broadcast at 25 mW, then interface on Nd4's reception from Nd3 will be high, leading to the loss of packet. Thus disproportional use of one node's power may result in the disfunctionality of other nodes. Thus power control also helps to enhance the traffic carrying capacity.

2. Related work

Alexiset al. [10], gives the survey on graph theory-based topology control methods. Each modelling follows one-hop connectivity and maximum node degree unbounded $(n - 1)$. Relative neighbourhood graph (RNG), has an edge uv if and only if $||uv|| = 1$ and the intersection of two open disks centred at u; v with radius $||uv||$ contains no node w element of V. The basic idea of the practical topology control algorithm is that every node orders its neighbours (set of nodes in the maximum transmitting range) according to a criterion (e.g., link quality), every node transmits its order at maximum power, based on its own order, and, on the orders of its neighbours, every node determines the set of 'logical' links according to a simple rule. This type of topology control algorithm is given in [11–13], used to abandon long distance neighbours.

Blough et al. [8] proposed a k-Neigh protocol for symmetric topology control in ad hoc networks. K-Neigh is a topology control algorithm based on the number of neighbours and neighbours bounded by a specific value K. Nodes do not know their positions; they simply calculate the distance between themselves and their neighbours. This assumes a continuous communication range and defines it until it reaches k-neighbours. The estimated preferred value of k that guarantees connectivity of the communication graph with high probability 9. Wattenhofer et al. [9,14], proposed a distributed approach for topology control named CBTC. Here node u transmits with the minimum power $P_{u,\alpha}$ required to ensure that in every cone of degree α around u, there is a node that u can reach with $P_{u,\alpha}$. Network connectivity is preserved by taking $\alpha = 2 * \mathrm{pi}/3$.

The need for CBTC arises when using GPS, which does not work in indoor environments. CBTC requires only directional information; it must be possible to estimate the direction from which another node is transmitting. Directional information is found out from directional antennae. CBTC is relay region based, and may have received the most attenuation. Nodes know information about their neighbours based on their relative signal strength and the signal arrival angle. Analysis of a minimum spanning tree (MST)-based topology control algorithm is given [15]. Building of a connected global MST-like topology with only bidirectional links occurs in a localized way. The topology constructed preserves the network connectivity. The

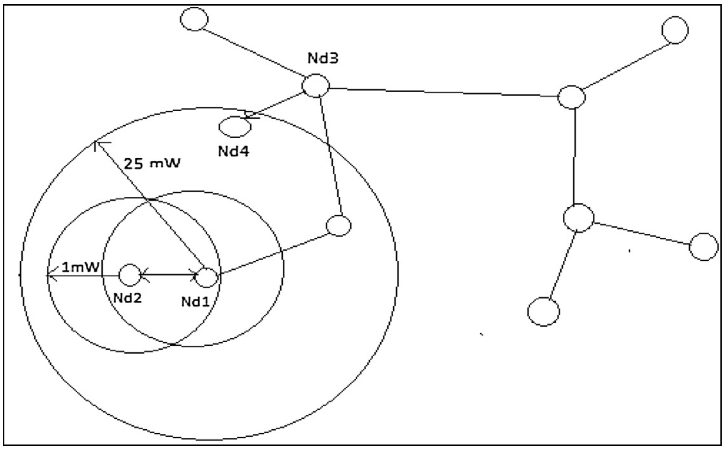

Fig. 1. Necessity of DTN topology control.

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degree of each node is bounded by 6. In LMST-built MST-like topology, the traffic load and the transmission power distributions for each node are greatly unbalanced. As a result, the energy consumption of the node is badly unbalanced so that the network lifetime is limited. A protocol that attempts to determine the CTR for connectivity in a distributed way is shown in [16,17]. Nodes maintain a routing table for each power level and set as the common transmit power, which is the minimum level maintained in all the corresponding routing tables containing all the nodes in the network. Common power protocol requires global knowledge (routing table) and it is affected by considerable messages overhead.

In [18,19], consider the limitations of node hardware and channel characteristics. This protocol needs knowledge about neighbours and provides eligibility metrics to ensure that the selected relaying nodes have a sufficient amount of energy to forward the packets. In DTNs, all nodes can establish a link with each other, creating a mesh topology network, which may not be power efficient. Another problem is that during the operation of the network, some nodes may exhaust their power more rapidly than others, while some may become dysfunctional. A topology control protocol [20–23] deals with all of these dynamics and ensures that the network is connected with power efficient links.

3. Proposed work: SH approach

3.1. Protocol description

Let V be the vertices set and E be the set of edges (communication links). Then the network graph is denoted as $G = (V,E)$. Each node $i \in V$ has its own position coordinates and identity (id_i). Edges between two nodes i and j are represented as $i \to j$ or $j \to i \in E$ and the distance between them is denoted as $d(i,j)$. Initially, every node broadcasts its possible parameters (node degree, link bandwidth, etc.) to its one-hop neighbour. Upon receiving broadcast messages from other nodes, every node keeps track of its neighbours and their strength, storing the estimated distance for each of them. After all the initial messages have been sent, every node in the network knows its neighbour's strength. The strength of the neighbour is the time-varying function and it should be maintained throughout the information exchange process. To achieve this, SH (SH) nodes are identified between source and destination pairs.

Given this information, every node computes its neighbour's parameter list, S_p (source parameters) and broadcasts this information. By exchanging neighbour parameters, SH nodes are able to determine which one is suitable for communication. At the end of the protocol execution, SH_p (SH node parameters) contains only eligible neighbours parameters 'p' in the final topology and 'p' is set to the minimum value needed to reach the farthest node in D_p (destination parameter). This value can be measured by either the received signal strength or distance, or alternate paths to the farthest node in G.

3.2. Properties of SH approach

- Correctness: if all the nodes use the same node degree (if node degree = 2, one forward and reverse link) or with static topology, the wireless domain is symmetric, then the SH approach computes the subgraph with suitable parameters. If the node degree is asymmetric, SH performs localized computation for selection of suitable parameters. To be precise, the SH node computes a subgraph path, where every node is connected to its SH neighbours, or to the maximum possible number of neighbours within the maximum transmitting range.
- Connectivity: under the assumption that nodes are distributed uniformly at random in graph G, each node is connected with high probability in G with a SH manner and the topology graph is generated.
- Bounded node parameters: the neighbour parameters of any network node at the end of SH protocol execution are upper-bounded by a factor N.
- Complexity: since every node in the network sends unidirectional messages, the total number of SH nodes is the order of $n\log(n_{SH})$, where n is the number of nodes.

3.3. SH algorithm

```
SH node estimation (stable phase):
1: Initialize $G_{SH} \leftarrow G$ // load the initial topology
Case I. SH node Selection: (source)
2: For each $i \in V$ // $i$ is the source
3: $P(i) \leftarrow [L]$ // initialize the parameter list
4: For each $j \in$ SH ($i$) // find out the SH neighbours of node $i$
5: SH($i$) $\leftarrow T_{SH}(i,j)$
// node support Tree ($T_{SH}$) structure and compute node $i$ and its neighbour SH
Case II. SH to SH neighbour estimation: (Intermediate/Destination)
```

(continued on next page)

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```
6: Set $T_{SH}(i) = T_{SH}(j)$ // connect SH neighbours till reach the destination node $k$.
7: For each $T_{SH} \leftarrow i$ // maintain unidirectional flow
8: $T_{SH} \leftarrow k$ // connect with destination
Case I and II are applicable for stable topology
Mobile phase: (for connectivity)
9: For each $i, j, k \in V$
10: For each $i, j, k \in T_{SH}$
11: If $[i \rightarrow j] \in T_{SH}(i)$ and $[j \neq i] \in V$ // connectivity between $i$ and $j$ not maintained
11: Remove $j$ from $T_{SH}(i)$
12: Add $[i \rightarrow l] \in T_{SH}(i)$ // $l$ be the member of $T_{SH}$
```

SH nodes generate a topology with upper bounds on the parameter in the order of N. The message overhead needed to build the SH method is smaller than that needed to build the MST-based graph. Given the same mobility pattern, the SH should be reconfigured much more frequently than the MST graph.

3.4. Theoretical analysis

A network is constructed with tree-structured nodes (SH nodes). SH nodes are able to find a subgraph for alternate routing during link or node failure situations. Assume the network topology remains connected and stable for a period of time, the collection of all nodes resulted from the SH protocol forms a tree structure. After the SH node election and tree construction phases, a set of disjoint leaf nodes and SH trees will be created. The nodes in these trees together form a tree set. The neighbouring SH-hops are used to determine the alternate path between one-hop neighbours based on the available parameters. Let a SH node formed by at least node degree n. At most n nodes are added with S_H node at each stage in subgraph G' (alternate routing node set). Suppose S_H is the fusion node and l is the leaf node with following subset in G. Let $S_{H1}, S_{H2}, \ldots, S_{Hn}$ and $l_1, l_2, \ldots, l_n$ be the subset of G. If two l nodes follow the same one-hop connection and the edge of S_{H1} and l is removed from the graph G, connections are maintained via S_{H22} (during the absence of originating S_H node). Since G be a connected graph and S_{H2} connects both source and other l nodes within the coverage area. Similarly if the network follows n-hop connection each node connection is maintained via neighbouring S_H nodes without looping problem. Hence connectivity is maintained.

Consider a SH node able to connect n nodes in k-hop. Let S_H, $T_{SH}(n)$, and l be the hierarchical structure for SH, tree-structured and leaf nodes respectively. If S_{H1}, S_{H2}, $S_{H3}, \ldots, S_{Hk}$ are the number of SH nodes in the network able to connect one-hop i node (source) within the coverage area. The value of addition of the 'n' nodes with T_{SH} set must obey the relation; i.e. $S_{H\Delta} \leqslant T_{SH\Delta} \leqslant n\Delta$ (one-hop connection), where Δ-is the node parameter. The maximum number of the node connectivity of the T_{SH}^{th} system is given by $T_{SHi} + S_{Hi} << n_i$, for $i = 1, 2, 3$. The connectivity of a network is defined as the probability of the number of one-hop S_H nodes connecting another leaf and S_H node in the graph.

4. Unstable Topology Structure approach (Power Efficient Topology Control—PETC)

Given a network topology of n nodes randomly placed in Euclidian plane, let V be the vertices set and E be the set of edges (communication links). Then the network graph is denoted as $G = (V, E)$. Each node $i \in V$ has its own position coordinates and identity (id_i). Edges between two nodes i and j is represented as $i \rightarrow j$ or $j \rightarrow i \in E$ and distance between them is denoted as d_{ij}. The set of neighbours of i, with which i is directly connected, are denoted as the set $N(i)$ and defined as $N(i)$: $[i \leftrightarrow j] \in E_{digraph}$. Let NL($i$) be the neighbour table list in which the state of each i in $N(i)$ is stored. NL(i) contains the identity, energy reserve, eligibility parameters, and required transmission power to reach each neighbour. Each node has a maximum transmission power of P_{max} and can assign varying transmission powers corresponding to each neighbouring node. The transmission power from node i to j is denoted as P_{i-j}. The residual energy of a node i at time t is denoted as e_i. Furthermore, all nodes start with equal initial battery capacity E. Communication in the network takes place over a wireless channel in which the transmitted signal is attenuated over distance. For an arbitrary node i, the position of a neighbouring node can be expressed in terms of its deviation from the optimal relaying position. The optimal relaying position is the direct line that connects node i with the base station. Taking i as the origin of the coordinate system, the x and y coordinates of node j are 'a' and 'b' respectively. Hence, $d_{ij} = (a^2 + b^2)^{1/2}$.

4.1. Network description

The network model describes the weighted two-dimensional planes for any arbitrary node in the network. The weighted region defines the degree of eligibility of a neighbour node to be a relaying node. PETC computation of eligibility criteria is performed by taking only local information into account. Minimization of the overall power cost of a multi-hop communication and reducing the disconnected links that occur due to disproportionate power consumption by individual nodes

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occurs. A transmitting node's knowledge is limited to its neighbours. Accordingly the efficiency metric (E_f) is applied to enable a node to compare and select a neighbour that can participate in building a multi-hop link whose overall power consumption is at a minimum. The eligibility of being a neighbour node j is calculated according to:

$$E_f = d_{ij} \cdot k / d_{ij}^k + K - 1 \tag{1}$$

Here K is knowledge about the neighbour, if $K = 1$, only one hop neighbour information is shared. The metric defined above is a measure of an efficiency of relaying nodes. We also considered the fairness between the nodes. In order to ensure that nodes use their power properly, nodes with relatively low power consumption are selected as relaying nodes. We thus define an eligibility metric (E_m), similar to an efficiency metric, which is also applied to a neighbouring node to measure its power usage with respect to other nodes. The eligibility metric is given as:

$$E_m = e_j / E \tag{2}$$

In order to compute the nodes with high power levels, this eligibility metric is converted to corresponding power (P_{ij}) as:

$$P_{ij} = E_m / t \tag{3}$$

Combining the efficiency metric and power eligibility metric through common eligibility metric (m_j) of a neighbouring node is written as:

$$m_j = E_f / P_{ij} \tag{4}$$

According to this value, each node sets its transmitting power to get the eligible neighbours, and with these neighbours the network connectivity is maintained. This protocol also checks for symmetric links. The detailed description is as follows.

4.2. Algorithm for topology structure

```
Phase 1: Identifying neighbours (for a generic node $i$)
    $G_j \leftarrow [id_i, (x_i, y_i)]_{Pmax}$: Node $i$ broadcasting its identity ($id_i$) and location information at maximum power to its neighbours.
    $G_i \leftarrow [id_j, (x_j, y_j)]$: Node $i$ receives information from $k$-Neighbour nodes and stores it in their neighbour lists, $N(i)$.
    $d_{ij} = [(x_j - x_i)^2 - (y_j - y_i)^2]^{1/2}$: Node $i$ calculates the distance to each neighbour nodes.
    Node $i$ calculates $m_j$, for each neighbour in its list.
    $E_f = (d_{ij} \cdot k) / \left(d_{ij}^k + K - 1\right)$
    $E_m = ej/E$
    $P_{ij} = E_m/t$
    $m_j = E_f . P_{ij}$
    Calculate the power required.
    $P_{th} = (P_{i \to j})_{min}$: Calculate the threshold power to correctly receive the message from the received power. Threshold power is the minimum power to reach the nearest neighbours.
    Node $i$ chooses the $k$-Neighbours in its list $N(i)$ that have the highest value of eligibility metric. If originally node '$i$' has less than $k$-Neighbours, then all nodes are chosen.
    $0 \leqslant P_{th} \leqslant P_{max}$: If there is no neighbour in this, then transmitted at its maximum power itself.
Phase 2: Building symmetric links (for a generic node $i$)
    $E = \{[i \leftrightarrow j] || [i \rightarrow j] or [i \leftarrow j]$: Node $i$ makes a bidirectional link between itself and its neighbours by checking neighbour list of '$i$'s neighbours.
    If node $i$ is present in their neighbour list then link is established otherwise that link is removed.
```

PETC follow two phases: (1) neighbour identification phase and (2) symmetric link check. In the first phase, initially each node broadcasts its identity and location information at maximum power to its neighbours and at the same time receives information from neighbouring nodes and stores it in its neighbour list. After identifying the neighbours, each node computes the distance to its neighbour's Euclidean distance method.

Each node calculates the common eligibility metric by finding the efficiency metric and power eligibility. Calculate the threshold power that to correctly receive the message from the received power. Threshold power is the minimum power needed to reach the nearest neighbours. Each node chooses k-Neighbours in its list that have the highest value of node eligibility metric. If node i has less than k-Neighbours, then all nodes are chosen. In the second phase each node checks for symmetric links between its neighbours. If a node i has a link to its neighbour j, then whether there is any link existing between node j and i is checked. If the link is existing bidirectional then that neighbour node and corresponding link are maintained, otherwise both link and neighbour node are removed from node 'i' neighbour list and the neighbour list is updated.

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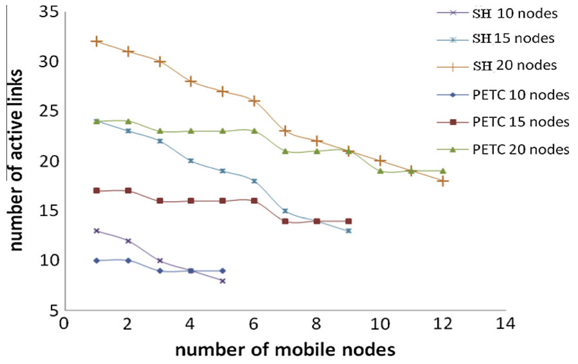

Fig. 3. Connectivity for various mobile networks (localized structure analysis).

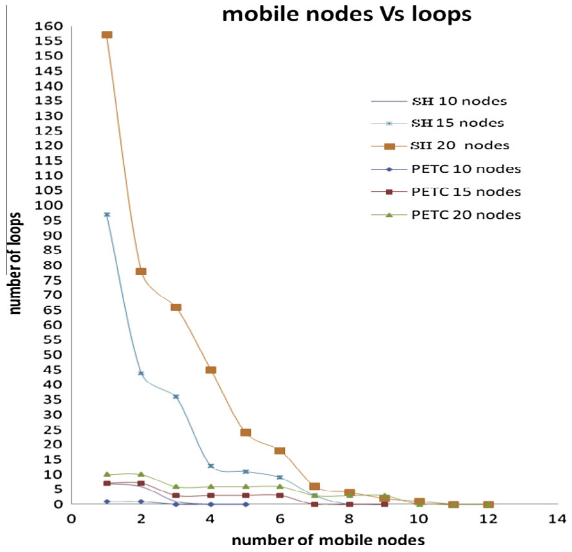

Fig. 4. Number of loop reduces as mobile node increases (localized structure analysis).

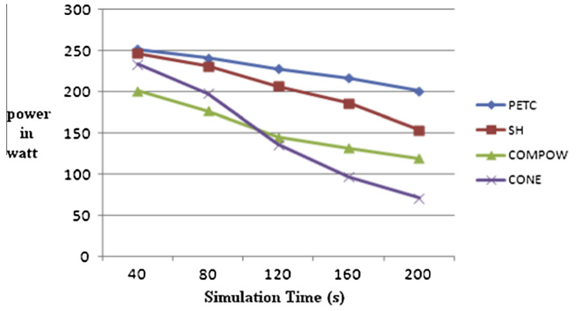

Fig. 5. Power variations during the simulation.

Topology structure node degree = (Active Link – Active Loop)/Total nodes. From the result, it is found that 20–90% node degree is required for subsequent structure constructions for mobile nodes. For example (consider the values from Table 2), for mobile node 5, SH active links –36, loops –28 and node degree ratio = 36–28/15 = 0.53. From this analysis, number of nodes increases (from 1 to 4) in the localized structure, UTS requires a constant node degree of 80%, and SH needs a gradual increase in the node degree. Since the mobility increases, virtual node density also increases, and a small number of nodes

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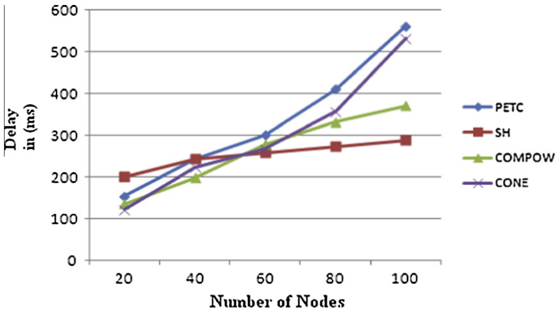

Fig. 6. Average end-to-end delay vs. network size.

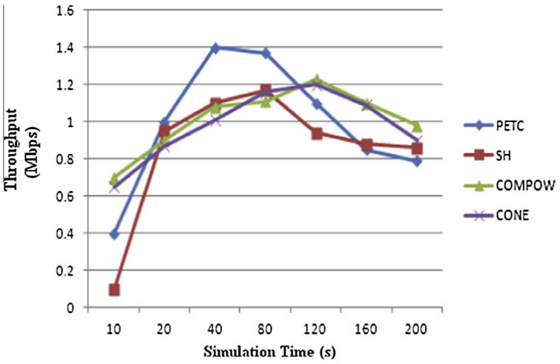

Fig. 7. Throughput during the simulation.

Table 2
Node degree requirements SH and UTS.

Total number of nodes	Total number of links	Number of mobile nodes	Number of active links		Number of loops		Percentage of node degree ratio for SH construction	Percentage of node degree ratio for UTS construction
			SH	UTS	SH	UTS	Active link – active loop/total number nodes	
15	40	1	15	17	12	7	0.2	0.46
		2	18	17	14	7	0.26	0.66
		3	19	16	14	5	0.33	0.73
		4	20	16	14	3	0.4	0.86
		5	36	16	28	3	0.53	0.86
		6	44	16	34	3	0.66	0.86
		7	54	14	43	0	0.73	0.93
		8	14	14	0	0	0.86	0.93
		9	13	14	0	0	0.93	0.93

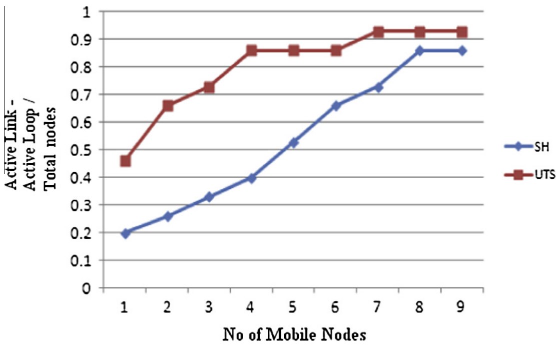

Fig. 8. Node degree requirement of SH and UTS.