Loner Links Aware Routing and Scheduling in Wireless Mesh Networks

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***Abstract*—In Wireless Mesh Networks (WMNs), TDMA based link scheduling can allow multiple concurrent transmissions, resulting in throughput improvements. In this paper, we identify certain link characteristics which reduce achieved spatial reuse and increase schedule length. It is shown that certain links (called *loners*) based on their length and position, introduce inherent difficulty in scheduling them with other links in network. Effects of such links on scheduling reveals important limitations of any such scheduling algorithm and motivates need of joint routing, scheduling and power control. We then present joint routing, topology control and scheduling algorithm to alleviate effects of loner links. Simulation results confirm throughput improvement with shorter schedule length.**

I. Introduction and Problem Description

Two contradicting power control strategies for WMNs are proposed by *short-range multi-hop* COMPOW [1] and *long-range single-hop* DirectTrans [2]. In COMPOW, all nodes use a uniform constant power level which is minimum required to maintain network connectivity. COMPOW achieves better concurrency in link scheduling but requires more number of transmissions per link with longer routing paths. In sharp contrast to this, in DirectTrans, nodes willing to transmit increase their power level until receiver can be reached in single hop. DirectTrans benefits from fewer transmissions and lower end-to-end delay but suffers with lower spatial reuse due to long higher interference links.

WMNs can be modeled as communication graph $G = (V, E)$, where $V = \{v_1, v_2, ...v_n\}$ represents set of n mesh routers located based on any arbitrary distribution in Euclidean plane. Every node in the network has the ability to vary its transmission power level continuously over a wide range. In DirectTrans [2], every node willing to send data uses just enough transmission power to reach the receiver in single hop and topology may result into a *clique*. Every node in network has *transmission range* (RT) and *interference range* (RI) associated with it. With DirectTrans mechanism, RT_{xy} reflects the length of an active transmission link xy and $RI_{xy} = \sigma \cdot RT_{xy}$, where interference ratio $\sigma > 1$. We define and use following *binary* interference model in this work:

$4-$*way Link Interference Model:* Simultaneous transmissions on two links uv and xy results into collision-free data reception at the receivers if and only if $d_{ux}, d_{uy}, d_{vx}, d_{vy} > RI_{uv}$ and $d_{ux}, d_{uy}, d_{vx}, d_{vy} > RI_{xy}$.

This assures that transmission on two links do not interfere with each other, if and only if nodes u, v and x, y do not lie inside *Interference Double Disks* $(D_{RI^x_{xy}}) \cup (D_{RI^y_{xy}})$ and $(D_{RI^u_{uv}}) \cup (D_{RI^v_{uv}})$, respectively. Size of the *Double Disk* depends on *RT* which in turn depends on length of the link in DirectTrans mechanism. Traffic matrix Tr is $n \times n$ matrix in which a non-zero element Tr_{ij} denotes end-to-end traffic demand between source i and destination j. Once, central controller performs routing using Tr, it reduces to a per link transmission demand matrix, Tx (also edge set E) which is used for TDMA link scheduling. Link quality and transmission data rates are assumed to be unvarying and identical.

As shown in [2], decreasing average hop count using per-link-minimality condition is favorable for throughput and delay optimization in practical size networks. So, it is of foremost interest to design a scheduling algorithm for DirectTrans and extend it for joint routing and scheduling. In this work, we show that using DirectTrans mechanism introduces certain longer links in topology which limit reduction of schedule length below a certain limit. We characterize these *loner* links and investigate their impact on a scheduling algorithm. As shown in Fig. 1(a)., problems of power control, scheduling and routing are interrelated and should be addressed together. We study these interrelated problems for DirectTrans mechanism to eliminate the adverse effects of *loner* links.

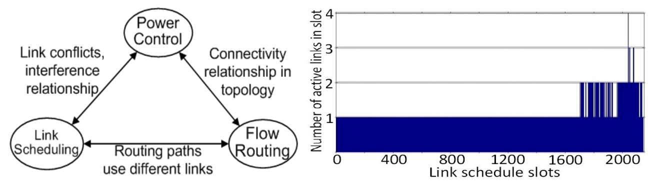
II. Scheduling Algorithm

If transmissions on two links interfere with each other, they should not be schedule in parallel in the same slot. For better spatial reuse and higher throughput, a scheduling algorithm should try to schedule as many links as possible in every slot. To capture the interference relationship between links, *conflict graph* (G_c) can be derived from communication graph G. G_c can be constructed by having a vertex for each edge of G. Any two vertices in G_c have an edge between them, if and only if their corresponding links in G interfere with each other. Problem of finding conflict-free schedule in G is then similar to problem of finding maximum independent set in G_c. In this section, we present a heuristic-based greedy algorithm for link scheduling which determines conflict-free feasible transmission schedule under $4-$way link interference model. Every link can be associated with an interference score which is the number of other links with whom it interferes and hence can not be scheduled simultaneously.

Greedy Scheduler shown in Algorithm 1 takes link transmission matrix and conflict graph as inputs and outputs a conflict-free schedule of link transmissions. For every slot, scheduler first chooses *base* link for transmission by *Criterion 1*. Once *base* link is selected, all link transmissions interfering with it are postponed for future slots. Remaining set of links still have the opportunity to be scheduled with *base* link in current slot. Out of these candidate links, another link is chosen by *Criterion 2*. This process is repeated until no more links can be scheduled in parallel in current slot. Maximum interference score is used as 1^{st} and 2^{nd} *Criterions* which selects links with highest interference score from remaining links in every step.

Algorithm 1 Greedy Scheduling Algorithm

Input: link transmission matrix Tx, conflict graph G_c
Output: conflict-free schedule $Sched_T$
Initialize: $Sched_T := \emptyset$
for all $Tx_{ij} \neq 0$, where $i, j = 1, 2, ..., n$ **do**
  choose link ij by *Criterion 1*;
  add link ij to $Sched_T$ in next available slot;
  let IL be set of interfering links as per G_c;
  for all $uv \notin IL$ **do**
    choose the next link uv by *Criterion 2*;
    add uv to $Sched_T$ in the current slot;
    update IL using G_c;
  end for
end for
return $Sched_T$



(a) Interdependencies of problems (b) Impact of loners on schedule

Fig. 1

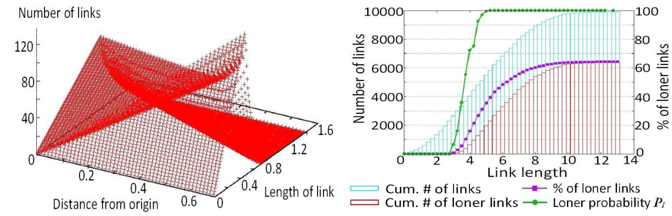
III. Loner Links

While scheduling links using greedy algorithm, majority of links give absolutely no opportunity of scheduling other links with them. We call such links to be *loners* in their slots. Formally, a link is called *loner* if transmission on the link interferes with all possible links of the network and no other links can be scheduled in parallel with it. Fig. 1(b). shows impact of loners in a typical schedule in random topology of 50 nodes having all-to-all unit traffic. Surprisingly, in majority part of schedule in Fig. 1(b)., only one active link can be scheduled in slot. A very few of such links are due to greedy nature of scheduler and we do not consider them as loners. Loners increase the overall achieved schedule length which reflects lower network throughput. So, it is important to analyze link characteristics which force a link to be loner.

Under DirectTrans mechanism, transmission range RT is equivalent to length of the link (L_l). Thus, interference range RI (with $\sigma = 2$) increases with the increase in link length, and more and more nodes get blocked by *Interference Double Disk* (IDD) when it is active. At a certain point, entire network area gets covered with IDD, raising the interference score of the link to be the highest and forcing it to be a loner. Using similar geometrical arguments, following lemmas characterize link lengths for loners in square and circular network area. Let, P_l be the probability that link l of length L_l is loner. Due to space limitations, proofs of lemmas are not presented.

Lemma 3.1: Given a square of side k units, any link of length $0.579k$ *or more is loner with* $P_l = 1$ *and any link of length* $0.304k$ *or lesser is not loner with* $P_l = 0$.

Lemma 3.2: Given a circular area of diameter d units, any link of length $0.485d$ *or more is loner with* $P_l = 1$ *and any link of length* $0.25d$ *or lesser is not loner with* $P_l = 0$.



(a) Link length and position (b) % of loner links

Fig. 2: Quantitative analysis of loner links

Loners can affect performance of any scheduling algorithm since its existence is independent of which scheduler is used. Loner probability P_l only depends on position of the link and its length. P_l is high even for a shorter link if it takes place towards the center instead of circumference because of more overlap between square area and IDD_l. Link position plays an important role only in the *gray zone* where $0.304k > L_l < 0.579k$. This shows that link position should also be studied along with length to find percentage of loner links in *gray zone*. Fig. 2(a). further elaborates this link length and position relationship with respect to total number of links in a unit square. It reveals that as link length increases from $0.304k$ to $0.579k$, larger fraction of the links are positioned toward the center, also increasing their P_l. It can now be estimated that probability P_l increases linearly between links of length $0.304k$ to $0.579k$. Summarizing, loner probability $P_l = 0$, when link length $L_l \leq 0.304k$, and $P_l = 1$ when $L_l \geq 0.579k$, while P_l increases linearly with length L_l in *gray zone* $(0.304k > L_l < 0.579k)$. Using this distribution of P_l to estimate total number of loners, approximately 60% links are loner links (with 0.02% error) in uniform topologies. Empirical data in Fig. 2(b). shows cumulative number of loner links with respect to link length in 100 nodes random uniform topology. As it can be observed, up to 65% of total links are loner and P_l increases linearly with link length in *gray zone*.

Considering all possible links using all-to-all unit traffic, up to 65% links can be loners. In presence of loner links, performing *just* link scheduling can not yield anything better than 65% throughput because achieved schedule is intrinsically dominated by links that can not be scheduled in parallel. Each loner link ends up occupying an entire slot for itself and therefore total achieved schedule length can not be reduced beyond total number of loners (65%).

IV. Joint topology control, scheduling & routing

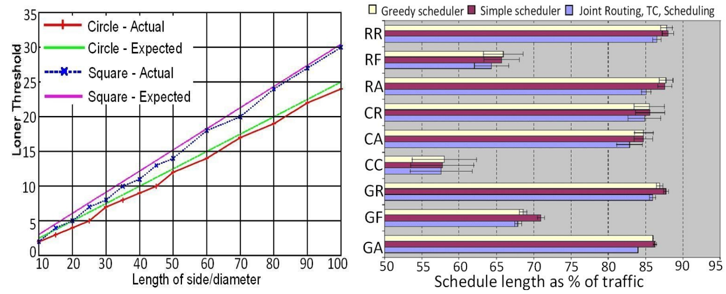
Performing *just* scheduling without consideration of power control and routing can yield limited results. In this section, we present joint topology control, scheduling and routing algorithm. As shown in Algorithm 2, topology control module shuns loner links to reduce interference. It eliminates loner links from the topology by comparing link length with $Limit_{TC}$ factor. As per *Lemma 3.1* and *3.2*, $Limit_{TC}$ is set to $0.304k$ for square network area of side k or $0.25d$ for circular area of diameter d. If the length of link is more than $Limit_{TC}$, it is a loner and its cost is set to infinite. After removing the loner links, it is important to route their traffic on different routing paths which use other shorter low-

Algorithm 2 Joint Topology Control, Scheduling and Routing

Input: traffic matrix Tr, link transmission matrix Tx, link conflict graph G_c, link length matrix Lx, link cost matrix Cx, auxiliary graph Aux
Output: conflict-free schedule $Sched_T$
Initialize: $Sched_T := \emptyset, Tx \Leftarrow Tr, Aux \Leftarrow \emptyset$
for all $Tx_{ij} \neq 0$ **do**
  choose link ij by *Criterion 1*;
  add link ij to $Sched_T$ in current slot;
  let IL be set of interfering links as per G_c;
  if there exists a link $uv \notin IL$ **then**
    for all $uv \notin IL$ **do**
      choose the next link uv by *Criterion 2*;
      add uv to $Sched_T$ in the current slot;
      update IL using G_c;
    end for
  else
    call TOPOLOGY_CONTROL module; {/*Loner*/}
  end if
end for
return $Sched_T$
TOPOLOGY CONTROL MODULE:
if $Lx_{ij} > Limit_{TC}$ **then**
  Set $Cx_{ij} \Leftarrow \infty$;
  if NETWORK_DISCONNECTED **then**
    undo change in Cx_{ij}; **return**
  end if
end if
call ROUTING module; **return**
ROUTING MODULE:
construct auxiliary graph using links with $Tx_{uv} = 0$;
find routing path between i and j using all links $uv \in Aux$;
update Tx for links of routing path; **return**

interference links. Different from loners, links on such paths will give higher opportunity of scheduling other links in parallel, which ultimately leads to shorter schedule.

As link scheduling goes along, traffic on many links get satisfied. Such shorter links could have been scheduled in future slots but were never scheduled simply because they had no unsatisfied demand. All such links can be used to build an auxiliary graph in every slot. Traffic on longer loner links can then be routed using shorter links of this auxiliary graph. Such shorter links can achieve better spatial reuse than loner links and therefore schedule length is reduced. As in Algorithm 2, whenever a loner link is encountered, topology control shuns it from topology and calls routing module to find a routing path. Routing module builds the auxiliary graph and finds shortest path for loner endpoints. It updates the transmission matrix for links of new routing path for further link scheduling and returns to scheduling phase. If such an auxiliary graph is disconnected and does not yield end-to-end routing path, minimum interference score can be used as the 1^{st} *Criterion* in scheduling. This way more number of shorter links get



(a) Expected and actual loner threshold in square and circular network area

(b) Comparison of simple scheduler, greedy scheduler and joint algorithm

Fig. 3

satisfied initially and they can be utilized for routing loners' traffic in later part of the schedule.

V. Numerical Results

Simulator uses grid (G), uniform random (R) and clustered (C) topologies with random (R), clustered (C), falling (F) or all-to-all (A) traffic patterns and maximum interference score as *Criterions* in square network area. In clustered traffic pattern, intra-cluster traffic is assumed to be higher than inter-cluster traffic. Falling traffic pattern assigns traffic on a link which is inversely proportional to its length. All-to-all identical traffic pattern establishes all possible links. Traffic demand is represented in terms of required TDMA slots. Relatively simpler scheduler which uses maximum traffic as *Criterions* is used as reference for comparison. Fig. 3(b). shows performance comparison between simpler scheduler, greedy scheduler and joint algorithm for 49 nodes network with different XY combinations, where X and Y represents topology type and traffic patterns respectively as mentioned at start of the section. Falling traffic benefits from low traffic on loner links and achieves shortest schedule. All-to-all traffic establishes high number of active links, reducing the performance of the scheduler. Inter-cluster links are loners with higher probability than intra-cluster links which is reflected in very short schedule length of CC combination. In all cases, joint design achieves shorter schedule than greedy scheduler because of loner links aware routing. Loner threshold analytically proven in *Lemma 3.1* and *3.2* is verified using experiments in Fig. 3(a).

VI. Conclusion and Future Work

Loner links can impair performance of scheduling, which makes joint routing, scheduling and power control necessary for throughput improvement in WMNs. Though results of joint design presented in this work do not yield significant performance increase, it is part of our ongoing research to design more comprehensive joint algorithm. This also opens new directions for systematically comparing COMPOW and DirectTrans power control trade-off with more realistic SINR interference model, which is also our continuing research.

References

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