Literature Study Notes

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1 A Survey of Network Design Problems and Joint Design Approaches in Wireless Mesh Networks

1.1 Thoughts

- Papers for first generations scheduling algorithms on simplified graphs might be useful.
- CSMA techniques might be useful, can "ping" a heralding station to detect when the link medium is free.
- By "hardwiring" certain repeater protocols along subpaths the requirements for "relatively stable" demand on the subpath may satisfy requirement for TDMA scheduling and achieving maximum throughput.
- For the single qubit case it may be possible to model as a matching problem or set covering problem.
- Refs 135 and 136 may provide some ideas on converting a centralized algorithm to a distributed one.

1.2 Notes

- References 49 through 58 may be useful for link scheduling, channel assignment, routing.
- Sections 4, 5 and 6 deal with link scheduling, channel assignment, routing.
- Link scheduling estimates the interference conflicts between the links having transmissiondemands (based on the interference model) and tries to achieve a conflict-free feasible transmission schedule.
- First generation of scheduling algorithms (refs 123-127) based on simplified graph models.
- When traffic is relatively stable (non-sporadic), TDMA can achieve maximum system capacity. Distributed implementation is substantially difficult and requires tight time synchronization. Relatively inflexible to dynamic changes to the topology. TDMA protocols can be categorized into course-grained and fine-grained protocols. Coarse-grained protocols emphasis given to link scheduling with various valid assumptions of interference model, traffic demands, and centralized control. Depend on existing link layer techologies for framing, acknowledgements, while handling medium access and transmission control at upper layers. Fine-grained TMDA protocols often handle all link layer functions at MAC layer, which makes then increasingly difficult to implement in practice.
- Reference 131 provides an LP formulation for node-based and edge-based spatial reuse TDMA scheduling for physical interference model.
- Reference 132 provided traffic controlled schedule generation algorithm.
- Important to model interference relationship between links based on respective interference model before they can be scheduled.
- Problem of link scheduling can be represented as a problem of finding maximum independent set in the conflict graph. Vertices connect to each other in the conflict graph represent those links of communication graph which interfere with each other and cannot be scheduled simultaneously.

- Reference 50 first designs conflict graph for protocol interference model indicating which set of links interfere with each other and cannot be scheduled together. Conflict graph in physical interference model has vertices which correspond to edges in communication graph. Directed edge between two vertices whose weight indicates what fraction of the maximum permissable no;ise at the receiver of one link by activity on another link.
- Conflcit graph based on interference model adds interference constraints to the LP formulation which optimizes throughput for single source-destination pair. LP formulation requires calculating all possible transmission schedules and it is shown to be computationally expensive.
- Reference 51 proposes a method to simplify the design of conflict graph in the physical interference model. The node-based conflict graph is designed by keeping the vertex set same as the communication graph and adding di;recting edges uv between vertices u and v whose weight corresponds to the received power at v from the signal transmitted by u. Only constraint is that node cannot transmit and receive on different links simultaneously.
- So this style forms a matching in communication graph. Propose an efficient polynomial-time scheduling approximation algorithm.
- Becomes increasingly difficult to estimate or even bound the optimal scheduler performance.
- Reference 134 derives a column generation method using set covering formulation which efficiently solves the scheduling problem.
- References 135 and 136 use netwrok flow problem and also provide a distributed scheduling algorithm.
- Channel/radio assignment mechanisms try to assign different non-interfering channels to the interfering links to increase overall spatial reuse. References 52 and 167 discuss import design issues and practical challenges while designing multi-channel protocols for WMNs. Channel assignment protocols can be broadly classified in static, dynamic, and hybrid schemes.
- Channel assignment problem can be modeled as edge-coloring of the network graph and related well-known heuristics or algorithms can be applied for the solution.
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2 GarQ: An Efficient Scheduling Data Structure for Advance Reservations of Grid Resources

2.1 Thoughts

- Discusses time-slotted data structures, segment tree. Provides a search algorithm for an available interval or nearest one.
- May be useful for an efficient implementation.

2.2 Notes

- Propose Grid advanced reservation Queue (GarQ) which is a new data structure that improves some weakness of Segment Tree and Calendar Queue. Demonstrate superiority of the proposed structure by conducting a detailed performance evaluation on real workload traces.
- Advanced Reservations allows users to gain simultaneous and concurrent access to adequate resources for the execution of applications.
- Tree-based data structures are commonly used for admission control in network bandwidth reservation (refs 3, 21, 23).
- Describe modified versions of Linked List and Segment Tree data structures to support add, delete, and search as well as the interval search operation capable of dealing with advanced reservations in computational Grids.
- Model composed of a reservation system responsible for handling reservation queries and requests, a grid consisting of a grid information service, resources, and users.

3 Link Scheduling in Sensor Networks: Distributed Edge Coloring Revisited

3.1 Thoughts

- When nodes in a quantum network are not attempting entanglement generation according to a TDMA schedule, they may focus on preserving entanglement or other local computations.
- Comparing to the edge coloring problem may be a useful approach.
- Problem is that all transmissions are assumed to take the same amount of time (1 slot). Could slots be made large enough to also have this type of affect. Could assign an edge multiple colors for each of the timeslots that it occupies?
- NP-Completeness of minimum number of timeslots ref 21 could be useful

3.2 Notes

- Consider problem of link scheduling in a sensor network employing a TDMA MAC protocol.
- Involves two phases, assign a color to each edge in the network such that no two edges incident on the same node are assigned the same color. Distributed edge coloring algorithm that needs at most delta+1 colors, where delta is the maximum degree of the graph.
- Second phase maps each color to a unique timeslot and attempt to identify a direction of transmission along each edge such that the hidden terminal and exposed terminal problems are avoided.
- Reference 5 discusses TDMA MAC protocols. These eliminate collisions, guarantee fairness and provie bounds on per-hop latency. To conserve energy, a node employing a TDMA MAC protocol can switch off its transceiver when it is neither transmitting nor receiving.
- References 6 and 21 discuss link scheduling.
- Edge coloring as a link scheduling problem - Valid timeslot assignment for nodes can be obtained by mapping each timeslot to a color. In wireless sensor networks this causes collision problems (probably not in quantum).
- Timeslot assignment to nodes is referred to as broadcast scheduling (refs 2, 20, 23).
- The problem of assigning timeslots to edges using a minimum number of timeslots is known to be NP-complete (ref 21)

4 On the Complexity of Scheduling in Wireless Networks

Sharma, Mazumdar, Shroff

4.1 Thoughts

- $K = 1$ hop problem may be related to single comm q case?
- Ref 30, Tassiulas and Ephremides characterized the capacity region of constrained queueing systems, develop a queue length based scheduling scheme that is throughput-optimal (stabilizes the network if the user rates fall within the capacity region of the network)
- References 34, 23, 22, 29, 7 show work in cross-layer optimization algorithms that try to consider multiple criteria like optimal routing, link scheduling, and power control.
- Changing conditions in wireless networks may be similar to how quantum devices need to be recalibrated and drift.
- References 16, 26, 3, 35 discuss fair resource allocation in wireline networks.

- References 4, 19, 21, 33, 28, 36, 24 incorporate congestion control frameworks. Congestion control component controls the rate at which users inject data into the network so as to ensure that the user rates fall within the capacity region of the network.
- Shows a general global optimization problem for schedulers in networks, these are known to be NP-Complete and Non-Approximable.
- Consider the Maximum Weighted K-Valid Matching Problems (MWKVMPs) that arise as simplifications to the scheduling problem.
- Node exclusive interference model for the single communication qubit case. Ref 11 has polynomial time link scheduling algorithm.
- Refs 4, 5, 19 have distributed link scheduling algorithm
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4.2 Notes

- Consider the problem of throughput-optimal scheduling in wireless networks subject to interference constraints.
- Interference modeled using a family of K-hop interference models defined as one for which no two links within K hops can successfully transmit at the same time.
- For $K = 1$ the resulting problem is the Maximum Weighted Matching problem which can be solved in polynomial time.
- For $K > 1$ show that resulting problems are NP-Hard and cannot be approximated within a factor that grows polynomially with the number of nodes.
- Show that for specific kinds of graphs used to model the underlying connectivity graph of wireless networks the resulting problems admit polynomial time approximation schemes.
- Simple greedy matching algorithm provides a constant factor approximation to the scheduling problem for all K in this case.
- Capacity of wireless links fluctuate due to fading, changes in power allocation or routing changes.
- Node exclusive interference model commonly used model for bluetooth and FH-CMDA networks. Only constraint on the set of edges scheduled to transmit is that it must constitute a matching.
- Reference 11 develops a polynomial time link scheduling algorithm under node exclusive interference model.
- References 19, 4, 5 developed distributed schemes that guarantee a throughput within a constant factor of the optimal.

5 Pinwheel scheduling with two distinct numbers

Holte, Rosier, Tulchinsky, Varvel

5.1 Thoughts

- Could be used for categorizing different types of traffic and using pinwheel problem.
- Other known results, every instance of pinwheel scheduling with density at most 3/4 has a solution, every instance with three distinct repeat times and density at most 5/6 has a solution. When there exists a solution an upper bound on the period is at most the product of the repeat times (exponential), not always possible to find a sub-exponential length schedule. With compact representation that shows distinct repeat times and number of objects with that time the pinwheel scheduling is NP-Hard.

5.2 Notes

- Interesting questions - Determining whether schedules exist, minimum cyclic schedule length, creating an online scheduler.
- Any instance with density $= \sum_{i=1}^{n} \frac{1}{a_i} > 1$ cannot be scheduled. Paper concerns element having only two distinct values.
- All such instances with only two values and $d \leq 1$ can be scheduled using a strategy based on balancing. Schedule created is not always of minimum length however. More complicated method used to create a minimum-length cyclic schedule. Both polynomial time algorithms but former much easier to compute than latter.
- Show how to use either method to produce a fast online scheduler.
- Minimum cycle length may be exponential in the length of the input (ref 2).
- Family of hard-real-time scheduling problems in refs 4,5,6,8,9. Periodic maintenance problem EXACTLY every a_i slots.
- Decision and scheduling problems for dense instances of up to three distinct numbers can be solved in polynomial time. Minimum schedule length is the LCM of the three numbers.
- Dense instances have interesting properites: Minimum schedule length for instances that can be scheduled is the LCM of distinct numbers. Slots assigned to item i must occuir exactly a_i slots apart. These and related properties do not hold for nondense instances.
- Multiset representation $\{x, a, y, b\}$ means there are a elements with frequency $a_i = x$ and b elements with frequency $a_i = y$. In this case we have $a > 0$, $b > 0$, $\frac{x}{a} > 1$ (because $\frac{a}{x} < 1$) and similarly $\frac{y}{b} > 1$. If dense then $\frac{a}{x} + \frac{b}{y} = 1$

6 TMDA Scheduling with Maximum Throughput and Fair Rate Allocation in Wireless Sensor Networks

6.1 Thoughts

- These types of protocols are called Media Access Control (MAC) protocols
- These papers always describe the model they assume for the network

6.2 Notes

- Propose network-wide optimized TDMA scheduling scheme for WSNs
- Formulate the rate allocation problem based on the Lexicographic Max Min (LMM) criterion which takes fairness, throughput maximization, and slot reuse into consideration.
- Develop a polynomial-time algorithm by exploiting iterative linear program to solve LMM optimization
- Maximizing sum of data rates (MSDR) of all nodes can easily lead to a baised rate allocation
- Exploit slot reuse to improve maximum throughput, introduce slot reuse control parameter ϵ in the LMM rate allocation problem. According to the optimal rate allocation vector and relay scheme derived from the LMM optimization, we then propose a TDMA scheduling algorithm, utilizing slot reuse, to achieve a minimum tDMA frame length.
- Slot reuse enables the improvement of the network throughput, the limited network bandwidth should also be considered. Develop a procedure combining the LMM rate allocation and the TDMA scheduling algorithm to iteratively calculate a proper slot reuse control parameter.
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7 Scheduling Algorithms for TDMA Wireless Multihop Networks Thesis

Peter Djukic

7.1 Thoughts

- Frame utilization is a good metric to look at.
- Is there an analogous way to view channel quality as done here?
- Notion of a conflict graph in network when resources are/not available for generating entanglement with neighbors. Thesis shows figures depicting different interference modes. 1) two nodes attempting entanglement with a node that only has one remaining resource, 2). So a static conflict graph might indicate nodes that do not have resources to support generating links on all connected edges, or it can dynamically be generated when assigning slots and showing which links can no longer be supported.
- Does routing provide a path or a protocol? Assume someone gives us a protocol, not an ordered set of edges because protocols may be more complex.
- Computation of requested link rates may be slightly different because it does not translate directly into the end-to-end rate of the connection. Depends on how many links need to be generated as part of the protocol. This could still be useful.
- Number of requested slots depends on the number of bits that can be transmitted per slot, in our case this is most likely less than 1.
- One of the main differences between our problem and classical networking scheduling is that packets can be stored and forwarded on any of the scheduled link transmissions in the future, whereas the entanglement generated NEEDS to belong to it's associated generated entanglement so that it can be used properly.
- Create new schedule with set of rates, do not try to keep the same slots occupied between frames.

7.2 Notes

- Link rates and resulting schedules are determined from end-to-end rates. Connections request their end-to-end rates and a scheduler grants end-to-end rates through a schedule. Since a schedule does not change between requests it is possible that schedule is temporarily not matched with the required end-to-end connections. (in 802.16 usually on the order of milliseconds.
- Frame Utilization ρ - The ratio of slots carrying traffic to the total number of slots in the data sub-frame.
- Goal is to find scheduling algorithms that minimize ρ given a set of end-to-end requested rates. Consistent with notion of finding minimum length TDMA schedules. Synonymous with maximizing end-to-end throughput.
- Model channel quality using the number of bits transmitted in each slot.
- Model conflict graph in the network that keeps track of interference of wireless links. Triplet $G_c(E, C, f_c)$ where E is the set of edges, C the set of TDMA conflicts, and f_c maps C to a set containing pairs of links that have conflicts.
- Assume that a routing protocol establishes routes between nodes and are represented with ordered sets of links (end-to-end paths in the topology graph).
- Given the requested end-to-end conection rates, find requested link rates by adding up connections traversing each link. Represent it with a vector of individual link rates.
- The number of requested slots for each link in the frame matches the requested link rate. Number of slots for each link in a frame matches the requested link rate ($\frac{r_j}{b_j}T_f$ where r_j is rate, b_j is bits transmitted per slot, T_f is the frame duration in seconds.)

- Duration of a link's transmission is then the number of slots multiplied by the slot duration.
- Link capacity constrains the achievable rate across all connections
- DAS problem like, calculate requested link durations based on requested rates, find a vector of starting times such that a schedule exists with the desired rates. Only tells us if there is/not a schedule.
- ML-DAS problem tries to maximize the durations with factor $\alpha \leq 1$ such that a schedule exists. By maximizing α we maximize the link durations. A feasible schedule might only be possble if we reduce the durations by some amount, by maximizing them we find the minimum length schedule that can satisfy the desired rates (reduced by the factor α).
- Techniques do not try to maintain the same set of slots between frames, if there is a new set of links we create a new schedule with the set of rates and send it out, so slot positions may change.
- Four reasons to solve the maximum concurrent flow problem, 1) Without delay constraints, problem viewed as the problem of finding the end-to-end "capacity" of wireless networks, 2) Corresponds to the "minimum length" or "maximum utilization" TDMA scheduling problem, 3) Optimization produces end-to-end rates that satisfy a limited proportional fairness property, 4) Method of framing the problem fits nicely into the 802.16 scheduling framework.