

A Cross Layer MAC with Explicit Synchronization through Intelligent Feedback for Multiple Beam Antennas

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Abstract—This paper introduces a novel cross layer medium access control protocol for multiple beam antennas to fully utilize their multiple-beam-forming capability. Our protocol, Explicit Synchronization via Intelligent Feedback (ESIF), uses feedback from neighboring nodes to synchronize data communication at multiple beams. ESIF exploits routing information to guarantee long-term fairness and minimize the energy and latency overheads. Unlike previous works on directional antennas that discuss range extension, we focus on optimal spatial reuse. Simulation results demonstrate that ESIF outperforms other on-demand access schemes based on IEEE 802.11 DCF for multiple beam antennas.

Keywords- Concurrent packet reception, medium access control, multiple beam antennas, multihop ad hoc networks.

I. INTRODUCTION

In recent times, multiple beam antennas have started gaining importance in wireless networks owing to their capability of supporting multiple data communications concurrently [1-4]. Using complex digital signal processing techniques an antenna array can support *either* multiple transmissions *or* multiple receptions simultaneously thereby considerably enhancing the system capacity. Such an antenna array is referred to as multiple beam adaptive array (MBAA) [5]. In this paper, we consider a wide azimuth switched-beam smart antenna comprised of multiple beam antenna array (SB-MBA) [2]. Such antennas with spatial multiplexing and demultiplexing capability present new challenges for medium access control (MAC) design in multihop wireless networks.

Conventional MAC protocols based on IEEE 802.11 Distributed Coordination Function (DCF) [6] cannot translate the capabilities of a multiple beam antenna into *concurrent packet reception (CPR)*. To achieve simultaneous transmissions or receptions, respective receivers and transmitters must initiate communication at the same time. However, *contention window (CW)* based random backoff timers in existing MAC protocols render the possibility of simultaneous initiation of communication improbable.

In this paper we present a new MAC protocol for multiple beam antennas which achieves CPR using feedback from neighboring nodes. Our protocol, *Explicit Synchronization via Intelligent Feedback (ESIF)*, removes the CW based backoff described above and uses the neighbor schedules to initiate

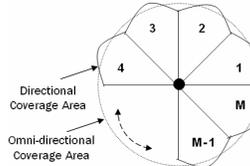


Figure 1. The antenna model

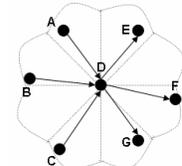


Figure 2. A sample topology

communication simultaneously at corresponding nodes. ESIF also uses the neighbor feedback to guarantee long-term fairness. Moreover, routing tables are exploited to minimize the energy and latency overheads. The present work shows gains from spatial reuse *exclusively* and not by extending the range of directional beams. Fig. 1 illustrates our antenna model. Note that the range is same as that of an omni-directional antenna.

The rest of the paper is organized as follows. In Section II we give an overview of the design issues related to MAC protocol for multiple beam antennas. In Section III we introduce our protocol, ESIF. The performance evaluation of the protocol is discussed in Section IV. The paper is concluded in Section V.

II. MAC PROTOCOL DESIGN ISSUES

A. Problems with existing MAC protocols based on IEEE 802.11 DCF for multiple beam antennas

1) *Concurrent Packet Transmissions/Receptions*: Multiple beam antennas allow either concurrent transmissions or receptions at a node. This requires:

- Packet receptions in different beams of the node to commence at the same time, which necessitates synchronization of transmitting nodes, and
- Packet transmissions by a node in multiple beams to begin simultaneously, which requires synchronization of receiving nodes.

Assume that in Fig. 2 nodes A, B and C need to send data to nodes G, F and E respectively, via node D. Without proper synchronization, nodes A, B and C will start data transmission at different time instants. The possibility that any two or all three of them will start their transmission at the same time is rare even if they have heard schedule of node D from control packets. This happens because after *distributed interframe space (DIFS)* duration, all transmitting nodes backoff randomly according to their contention windows. As a result, node D will receive only one packet - from the node that begins

This work has been supported in part by the Ohio Board of Regents, Doctoral Investment Funds and National Science Foundation Grant CCR-0113361

transmission the earliest. Furthermore, node D will have only one packet to transmit in the next cycle. Hence IEEE 802.11 DCF based protocols fail to utilize the entire potential of the antenna array Reference [1] discusses the possibility of CPR and CPT with such protocols in greater depth.

One trivial solution to receive multiple packets is to form beams in all directions in reception mode and continue listening on them until any one beam is engaged in data reception. However, this can lead to *transmission starvation*¹. Reference [2] suggests an alternate solution, where the receiving node waits in reception mode for a fraction of packet duration longer to catch receptions in different beams. Though this enhances the network throughput in one-hop communication, but in a multihop network the extra wait at each node will increase end-to-end latency. Another solution is scheduling based MAC schemes [3], [4] that require global or two-hop neighbor information. However, these schemes involve overheads from scheduling messages and topographical information. Reference [1] also suggests some guidelines for making best use of multiple beam antennas. However, no specific protocol is suggested.

2) *Hidden Terminal and Deafness*: Problems due to hidden terminals and deafness often arise with directional communication and have been thoroughly explained in literature [12]. These problems arise primarily due to inability of a node to gather information about the ongoing transmission(s) in its neighborhood.

B. Solution: ESIF Design Decisions

To allow *all* neighbors to update their schedules, a node should transmit control packets in all its beams. As a result, the neighboring nodes defer transmission(s) for the remaining duration of the ongoing communication. Thus omnitransmission of control messages alleviates problems due to hidden terminals and deafness to a large extent.

On the other hand, transmission of control packets in all beams may block data communication between a pair of neighbors which ideally could have progressed concurrently. It also requires more energy to send control messages in all beams. The protocol thus faces conflicting requirements; to reduce deafness, use more energy and block some possible communication; *or* to reduce energy consumption and allow more data transactions possible but suffer from deafness and hidden terminals.

Moreover, we eradicate the random backoff period after DIFS wait. This offers two major advantages: 1) transmitters are synchronized with the receivers; and 2) all the beams of a transmitter are synchronized. While the former greatly enhances the probability of CPR, the latter boosts the CPT probability. A node ready to transmit data in multiple beams checks the expiration of *directional network allocation vector (DNAV)* [7] settings, senses the channel for DIFS duration, and immediately begins data transmission in those beams concurrently.

However, removal of a random backoff leads to unfair award of the channel to nodes. For example, a node with very high data generation rate will overwhelm its receiver, without

giving latter a chance to forward this traffic. Moreover, multiple transmitters, located in the same beam of common receiver, will always get the same receiver schedule and initiate communication at the same time. This leads to data collision at the receiver. Note that IEEE 802.11 DCF does not suffer from this problem. The random nature of backoff ensures fair award of channel to each node. This brings forth an interesting paradox; preserve the backoff and lose performance, *or* discard the backoff to achieve CPR and suffer from unfair channel access.

In our protocol, ESIF, we propose an elegant solution to the aforementioned problems, by sending feedback to neighbors piggybacked in handshaking messages, and by using cross-layer information. Forearmed with the knowledge of routes and traffic availability, ESIF employs hybrid scheme to fulfill contradictory requirements in most cases. Details of ESIF follow in the next section.

III. THE ESIF PROTOCOL

A. Assumptions

The following assumptions are made while designing ESIF: (1) nodes are equipped with SB-MBA and can precisely calculate the Angle of Arrival (AoA) of the received signal [8]; (2) each node forms non-overlapping multiple beams with equal gain; (3) Beam shape is assumed as conical and the impact of side-lobe interference or the benefits of nulling are not considered; (4) the channel is symmetric.

B. Protocol Description

There exists a store-and-forward buffer at each node for relaying data packets. It is used as a first-in-first-out (FIFO) queue. We dynamically use the available buffer to form different queues for each beam. This prevents head-of-the-line blocking [9], gives a node precise control over its backlog, and helps send feedback into the network. Feedback is described in more depth later in this section. Every node maintains the following dynamic information about each of its neighbors:

- The beam the neighbor falls within
- Neighbor's schedule - the duration until this neighbor is engaged in communication elsewhere
- Whether the neighbor's schedule requires maintaining silence in the entire beam
- Number of data packets outbound for the neighbor
- The p-persistent probability to use when talking to this neighbor

The above information is stored in *ESIF Network Allocation Vector (ENAV)*, a concept that extends DNAV. Using the above information along with the personal routing tables a node can determine the following information:

- Whether a beam contains an active route
- The number of potential transmitters in each beam
- Until what time the node needs to maintain silence in a particular beam

We are now proceed with the mechanics of the proposed cross-layer MAC. ESIF is an on-demand channel access

¹Transmission starvation occurs when a node stays indefinitely in reception mode without getting a chance to transmit data.

scheme. It modifies the IEEE 802.11 RTS/CTS messages to piggyback feedback to the neighboring nodes. We call our modified messages *RTS with Intelligent Feedback* (RIF), and *CTS with Intelligent Feedback* (CIF). We use another control message, *SCH*, which is sent in all beams other than the ones being negotiated via RIF/CIF. Further, a node can use information from the network layer to determine which beams contain an *active-receiver-route* – beams with potential transmitters. The node saves its energy by sending SCH in only these beams. The node still listens to control messages coming in all the beams as they might be for route discovery or maintenance. The frame format for control messages is shown in Fig. 3. Here,

- *Duration* holds the estimated time of communication that the other nodes must backoff for;
- *Priority* contains the priority of this request; and
- *N* is the number of potential transmitters in this beam of the node. This is used to calculate the persistent probability which the other stations use when talking to this node.

All other fields retain their semantics as in IEEE 802.11 DCF. We recommend using the type field in *Frame Control* to identify a control message as RIF, CIF or SCH. An SCH identifier allows a neighbor to adjudge whether it lies in an active beam for the original transmitter. Thus a node can decide whether to defer transmission for all the nodes in this beam, or just for the node that sent the message.

The backoff time in *duration* field is used by all the neighbors to update their schedules pertaining to the node that sent the control message. Note that the field contains only the duration of remaining communication and not the exact time instants. Hence, this mechanism does not require a global clock.

We suggest calculating a *priority* for every data request/transmission on a beam. The priority is based on relative contribution of two parameters: the total number of outbound data packets on a beam (backlog), and the time the data packet has already spent in the network. These parameters together ensure *per-route fairness* when a node decides to communicate on a reduced number of beams in order to conserve energy.

We further propose using a *p*-persistent CSMA mechanism. Initially, the value of *p* for every neighbor is set to 1. This value is updated whenever a node receives new feedback from the corresponding neighbor. The value of *p* is the reciprocal of the number of transmitters, *N*, embedded in control messages. This mechanism solves the problems of channel contention when multiple transmitters exist in the same beam of a receiver as mentioned in Section II. A proportionally set probability also gives equal channel access to all transmitters. This ensures long-term fairness.

We also install a mechanism similar to hot-potato routing at every node. This not only minimizes the queuing delays in the network, but also creates a graceful method to switch priorities between receiver and transmitter roles. As long as a data packet exists in the queue, the node must give priority to the transmission mode. Otherwise, the reception mode supersedes.

Bits: 16	16	48	48	4	4	32
Frame Control	Duration	RA	TA	Priority	N	FCS

Figure 3. Control packet (RIF/CIF/SCH) format

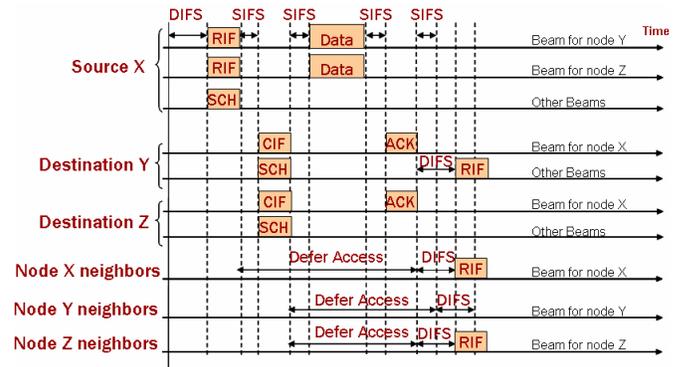


Figure 4. Basic operation of ESIF MAC

TABLE I. TRANSMITTER AND RECEIVER ALGORITHMS

Transmitter:	Receiver:
Find highest priority data beams	Collect all Control messages;
For every beam; do	Update schedules from CIFs/SCHs;
If the schedule permits traffic;	If Receiver has priority;
Send RIF on data beams	If valid RIF;
SCH on other beams	Find highest priority data beams
Collect all CIFs	For every beam; do
For every RIF sent; do	If schedule permits traffic;
If valid CIF;	Send CIF on data beams,
Send data packet(s)	SCH on other beams
Collect Ack	Collect data packet(s);
If valid Ack;	For every CIF sent; do
Remove packet from queue	If valid data; then
Else	Add packet to queue
Increase retry attempts	Send Ack
Else	If atleast one packet was received;
Increase RIF attempts	If receiver gets priority;
Set neighbor schedule	Idle wait SIFS duration
If receiver gets priority;	Return;
Idle wait SIFS duration	
Return;	

This priority switch creates *successive* cycles of concurrent packet receptions and transmissions thereby maximizing the utilization of multiple beam capabilities. Further, depending on the available neighbor and beam schedules, a node can determine whether it can actually initiate data transmission. If not, the reception mode can still be awarded the priority. The priority switch also solves problems of an overwhelmed receiver as discussed in Section II.

Table I presents the algorithms for the transmitter and receiver. In case a transmitter does not receive a CIF, it postpones the schedule for the appropriate neighbor using an exponential backoff similar procedure. Fig. 4 illustrates the operation of ESIF MAC. Assume that node X wants to send a packet each to nodes Y and Z. It sends an RIF to Y and Z and an SCH on all other beams containing an active route. All the neighbors of X update their DNAV from the durations in these messages. Similarly, the neighbors of Y and Z update their DNAV after listening to CIF/SCH from Y and Z respectively. Assume that nodes X and Z give priority to receiver modes after the current communication. Therefore, the duration field

of RIF/SCH from X (and CIF/SCH from Z) contains the time required for current communication. Also assume that node Y awards priority to transmitter mode. The duration field of CIF/SCH from node Y is SIFS duration greater than what the current communication would take. The neighboring nodes now have a schedule for Y that expires later than the time when Y is actually ready for next communication. As a result, after the current transmission, Node Y sends out control messages *before* its neighbors. This prevents node Y from being starved for transmission and being deaf to RIFs from its potential transmitters. The neighboring nodes of Y listen to RIF/SCH from Y during their DIFS wait and defer communication.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

The simulation is written in PARSEC [10], a C-language based discrete event simulator. Table II details some important simulation parameters. The simulations are run for different random seeds and the results statistically averaged out for five iterations each running for hundred simulation seconds. A free space path loss model is assumed. The power levels in Table II for various modes are the nominal values for the omnidirectional wireless LAN cards [11]. The power values for reception and transmission modes are divided by the total number of beams, eight, to obtain nominal values for each beam. As in several earlier studies [1], [4], we compare the performance of different MAC protocols under static topological conditions. The generation of packets at the source nodes is modeled as a Poisson process with the equal mean arrival time. Further each node has a maximum buffer of 30 packets and a *lifetime* of each packet as 30 packet durations after which it is considered as dead and is dropped. This sets an upper bound on the network delays in all protocols considered.

Apart from ESIF, we use three other protocols on the same topological scenarios to compare and contrast their performance. The protocol *Omni* essentially uses the SB-MBA as an omnidirectional antenna. *Directional-NB* uses the antenna array one beam at a time and *MMAC-NB* uses all beams simultaneously. *Omni*, *Directional-NB* and *MMAC-NB* are all based on IEEE 802.11 DCF mechanism [1]. All protocols use a unified backoff timer for all their beams. This maximizes the probability of CPT.

B. Simulation Results

The three metrics used to evaluate the performance of our protocol are network throughput, end-to-end packet delay and total energy spent in the system. We discuss the performance of ESIF with the aid of sample topologies (Fig. 5). The results show that ESIF outperforms all other protocols for multiple beam antennas in most cases. In topologies where multiple beams can be employed simultaneously, like in Topology 1, gains in throughput are enormous (Fig. 6). In these cases ESIF is able to achieve CPR at common intermediate nodes (node C here). Moreover, the dynamic priority switch ensures that the data packets just received are transmitted (concurrently) in the next cycle thus maximizing throughput and minimizing delay. We see that delays with ESIF are always lower than those in *Omni*, *Directional-NB*, and *MMAC-NB*; but they rise sharply

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Data rate	2 Mbps
Data packet size	2000 bytes
Control Packet size	45 bytes
Sensing power	0.07 mW
Reception power	1.45 mW
Transmission power	1.75 mW

at higher loads and are ultimately bounded by the packet lifetime. This happens because of network saturation.

Fig. 7 shows that ESIF enhances throughput by the priority switch between transmission and reception modes. ESIF ensures concurrent communication between nodes A-B, and C-D. This leads to large gains over a directional protocol which suffers from deafness in this case. Again, network delays rise sharply after saturation. Fig. 8 clearly shows that removal of contention window in ESIF does not affect *long-term fairness*. Both the transmitters get equal opportunity to transmit.

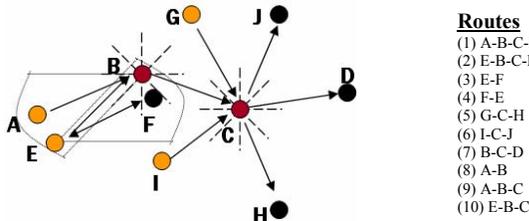
In Topology 4, when multiple transmitters exist in the same beam of a receiver, ESIF extracts the highest throughput among all protocols by using a proportional p value for persistent CSMA (Fig. 9). The results for *Omni* and *MMAC-NB* coincide with each other. In both these protocols, the intermediate node stays primarily in the receiver mode and drops most of the received packets when they live beyond their lifetimes. ESIF shows higher delays than directional protocol because while using p-persistent CSMA, a large fraction of time is wasted when either no transmitter contends for the channel, or when both transmitters contend for the channel.

In Fig. 10, we see that *Omni* and *MMAC-NB* outperform ESIF. This happens because in ESIF, both the source nodes are synchronized to send RIFs at the same time. This results in collisions at the receivers and a backoff at the transmitters.

Throughput of ESIF in random topology clearly outperforms all protocols under heavy load conditions and even under presence of hidden terminals as shown in Fig. 11. However, in a completely connected topology with 5 nodes, *MMAC-NB* shows better performance than ESIF at higher loads (Fig. 12). This is because ESIF uses tight synchronization and under heavy traffic, the chances of multiple receivers sharing the same schedule are remote.

The energy spent (Fig. 13) by ESIF is lesser than that by *MMAC-NB*, and approaches the figures for *Directional-NB*. This advantage comes from using the cross layer information – ESIF sends control messages only in beams where potential transmitters exist. Similar results for energy expenditure are observed in all other topologies.

The results in Fig. 6, 7, 8, 9 and 10 also show that the throughput is close to theoretical upper bounds. For example, in Fig. 6, there are three source nodes. Up to the arrival rates of 50 pkts/sec, a linear increase in the network throughput can be observed. The throughput is clearly about thrice the arrival rate at each source node in this region. The network goes into saturation beyond this point (For a two hop route, a maximum of 58 packets can reach a destination every second). Similar analysis can be performed for other topologies but scarcity of space prevents its presentation here.



- Routes**
 (1) A-B-C-D
 (2) E-B-C-D
 (3) E-F
 (4) F-E
 (5) G-C-H
 (6) I-C-J
 (7) B-C-D
 (8) A-B
 (9) A-B-C
 (10) E-B-C

Figure 5. Topologies used for simulation;

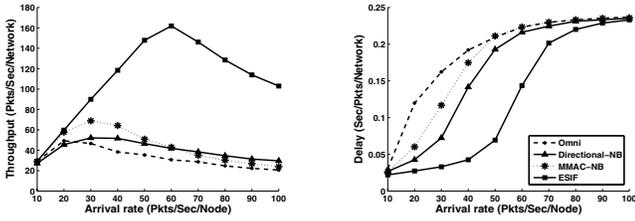


Figure 6. Topology 1 – B->C->D, G->C->H, I->C->J

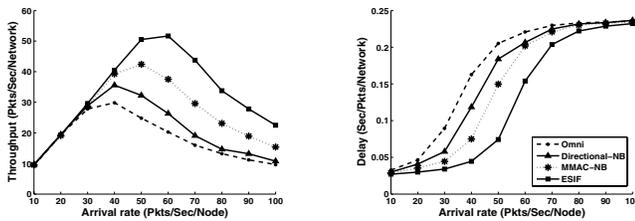


Figure 7. Topology 2 – A->B->C->D

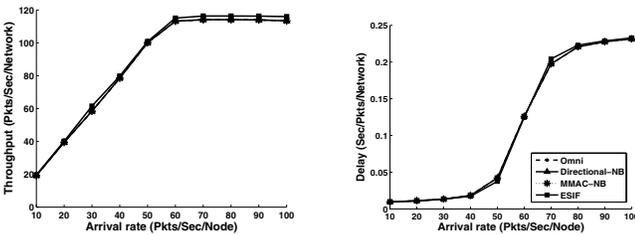


Figure 8. Topology 3 – E->F, F->E

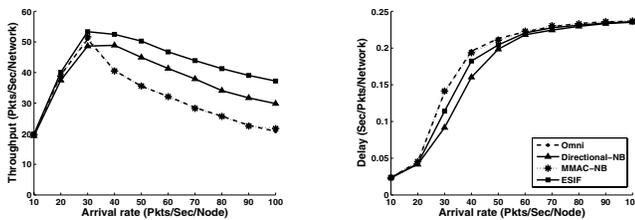


Figure 9. Topology 4 – A->B->C; E->B->C

V. CONCLUSIONS

This work proposes a novel MAC protocol, ESIF, for multiple beam antennas. ESIF removes the contention window based random backoff in IEEE 802.11 DCF based protocols and uses embedded feedback to synchronize neighboring nodes. ESIF thus allows nodes to receive (or transmit) multiple packets *simultaneously* in different beams. We believe that ESIF is the first attempt to achieve concurrent packet reception. Cross layer information is used to guarantee long-term fairness. Our simulation results show the superlative performance of ESIF over IEEE 802.11 DCF based MAC protocols for multiple beam antennas. We intend to further analyze the QoS guarantees over ESIF. Cases where multiple transmitters exist in the same beam of a receiver need to be investigated further.

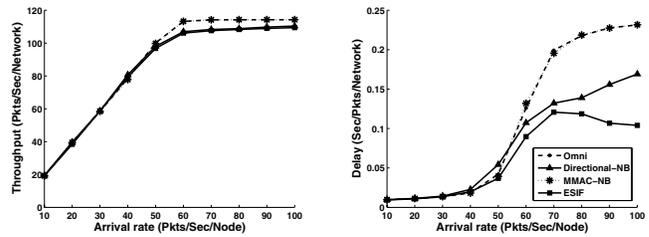


Figure 10. Topology 5 – E->F, A->B

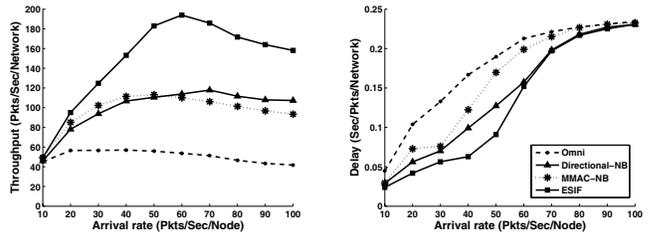


Figure 11. Topology 6 (with all routes 1 – 6 in Fig. 5)

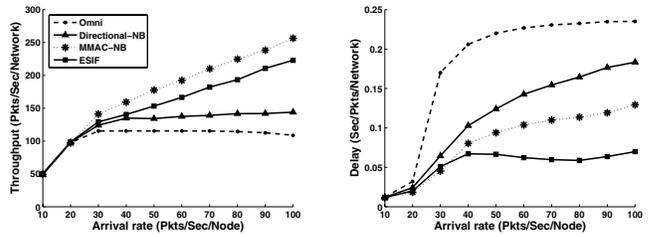


Figure 12. Topology 7 (Complete graph with 5 nodes)

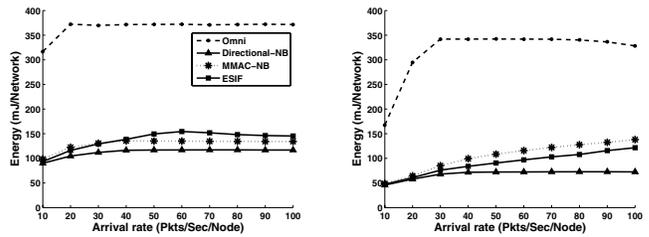


Figure 13. Energy spent in topologies 6 and 7

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