A Cross Layer Routing Metric with Wireless Cooperative Protocols

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Abstract

Cooperative link layer protocols are typically used in single hop networks. In such protocols, a special node called the *relay* node helps deliver frames from a source to a destination. The performance benefits of cooperation at link layer can be streamlined into multi-hop networks as well. In multi-hop networks, a frame is sent from an original source to the final destination through a series of *intermediate nodes*. The paper extends the expected transmission time metric — proposed for multi-hop wireless ad hoc networks — to the context of cooperative IEEE 802.11 link layer protocol. The designed metric is called cooperative expected transmission time (CETT). CETT carefully accounts for the higher probability of successful frame transmission and therefore the reduction in expected transmission time brought about by the relay node in the cooperative protocol. CETT jointly optimizes both the route computation and the selection of the cooperative relay at the link layer. Route optimization helps jointly choose the best set of intermediate nodes and cooperation optimization helps choose the best relay node for each link in the multi-hop. As a result, CETT helps distinguish the case wherein it is better to use a node as a relay as compared to using it as an intermediate node. For comparison, the case where cooperation is applied after route computation is also presented. Minimizing the expected transmission time may result in more efficient link utilization and increased overall end-to-end network throughput. It is also shown that joint optimization of route and relay selection is better than finding routes and then applying cooperation.

I. INTRODUCTION

Wireless channels are susceptible to fluctuations in terms of path loss, fading, etc. Wireless link layer protocols provide automatic retransmission request (ARQ) mechanisms to counter frame corruptions due to both frame errors and collisions. For example, in IEEE 802.11 medium access control (MAC) protocol, a transmitter can attempt to transmit a given frame multiple times, up to a predetermined maximum value, before moving to the next frame awaiting transmission. ARQ mechanism may be enhanced using cooperative nodes, as proposed by a number of authors [1], [2], [3]. In link layer cooperative ARQ protocols, a third node, namely the *relay*, helps deliver frames from source to destination. While the relay's intervention is regulated by specific rules — which vary from protocol to protocol — its cooperation can bring perceivable performance advantages in single hop networks [1], [2], [3].

Designing routing protocols for multi-hop wireless networks constitutes yet another challenge in terms of overhead incurred in establishing and maintaining end-to-end routes along multiple *intermediate nodes*. Several routing protocols have been proposed in recent years, e.g., [4], [5]. These routing protocols try to minimize the hop count — i.e., the number of intermediate nodes — in reaching the destination. It is well understood that the hop count metric may not be the best choice for wireless networks as multiple transmission rates are now available and different error probabilities for the corresponding rates may be expected. Some work has been done in this regard [6], [7]. One such proposed work — namely the expected transmission time (ETT) — attempts to minimize the expected air time that is consumed in successfully delivering a frame from the source to the end destination. Another metric — expected transmission time (ETX) — attempts to minimize the number of transmissions required to deliver a packet to the end destination. It is noted that ETT is bandwidth adjusted ETX [7].

The relay node can help lower this expected transmission time of a frame. Network layer may or may not be aware of the link layer cooperative protocol. Both these cases have been explored in this paper. In the case where network layer knows the existence of relays, the links in a route can be stretched as the relay node would compensate frame losses. On the other hand, when the network layer is unaware of the relays, route computation is done independent of relays and therefore converges to the same path as the non-cooperative case. However, link layer finds a suitable relay for each link.

When the network layer is aware of the underlying cooperative link layer protocol, there is no reason to exclude that cooperative protocols at the link layer and routing protocols may coexist in the same network. There is no evidence that the two combined network functionalities can yield any meaningful performance advantage. In fact, one could argue that in multi-hop networking a potential relay node may better function as intermediate node along the route.

In this paper the authors present a study to clarify this point, and possibly reach a conclusion about the usefulness of cooperative link layer protocols in multi-hop networks. Theorems are presented to demonstrate that not all cooperative link

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layer protocols are suited to work in multi-hop networks. For the cooperative protocols that are suited to work in multi-hop networks, a routing metric is then proposed, termed cooperative expected transmission time (CETT). CETT is defined to account for the overall transmission time required over a single hop, when taking advantage of potential relay nodes within hearshot. By adopting CETT as the routing metric, multi-hop routing protocols can then jointly optimize both the end-to-end route computation and the relay selection on each link (hop) along the path. A case study is presented to illustrate how CETT can be adopted in OLSR protocol [5]. While performance gains vary from topology to topology, simulation results indicate that the use of CETT based routing yields transmission time reductions and throughput gains as high as 50% when compared to conventional ETT based routing.

II. COOPERATIVE PROTOCOLS IN SINGLE HOP NETWORKS

This section briefly describes two families of existing cooperative link layer protocols, designed to function in single hop networks.

A. Transmission Time Advantage (TTA) Based Cooperative Protocols

Two cooperative protocols are based on the concept of TTA. CoopMAC II [1] is a cooperative protocol that aims to minimize the transmission time consumed to reach a destination, assuming that there is no retransmission in the channel. If there is a transmission time advantage in going through the relay node to reach the destination, CoopMAC II always uses the relay node to transmit the frame from source to destination. This is the case when both the source-relay distance and the relay-destination distance are such that higher transmission rates can be used there compared to the transmission rate available on the source-destination link. In CoopMAC II, once a relay node is chosen, any frame transmission from the source goes to the relay node first. The relay node then forwards the frame to the destination. The destination sends an acknowledgment (ACK) frame directly to the source in response. The details of the protocol can be found in [1].

A similar approach is used in rDCF cooperative protocol [2], which tries to minimize the transmission time to reach the destination. The difference between [2] and [1] is the protocol designed to choose the relays. However, once the relay is chosen, the same frame transmission sequence is used in the two solutions.

B. COBRA MAC Protocol

The COBRA MAC protocols [3] is a variation of the IEEE 802.11 in ad hoc mode. When two nodes exchange data frames over one hop, other nodes within transmission range may overhear the ongoing frame transmissions. One of these nodes may act as a relay as shown in Fig. 1. The relay stores a copy of the received data frame and then senses the channel after a timeout RIFS (relay inter frame space) defined in [3]. If the channel is sensed free, the relay makes the assumption that the intended destination has not received the data frame successfully and retransmits the same frame. On the contrary, if the channel is sensed busy, that indicates that the destination is responding with a positive acknowledgment, thus the local data frame copy at the relay is discarded. More details about the COBRA MAC are available in [3].

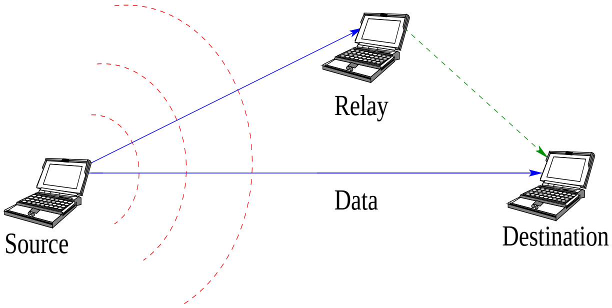

Fig. 1. COBRA MAC: relay cooperating in the unicast data frame transmission from source to destination

The main difference between the COBRA-MAC protocol and the TTA cooperative protocols is that relay is opportunistically required to help with the frame transmission only when the direct transmission attempt from source to destination fails.

III. COOPERATIVE PROTOCOLS IN MULTI-HOP NETWORKS

This section identifies which of the cooperative protocols defined in Section II is suited to work in multi-hop networks. The study is carried out assuming that ETT is the absolute performance metric to consider, i.e., the best protocol is the one which yields the minimum ETT value.

Consider three nodes S, R and D. Let S be the source, D the destination, and R the relay. The terms frame and packet are used interchangeably. The following notation is introduced:

- T_{sd} is the transmission time of data frame in S-D link,
- T_{sr} is the transmission time of data frame in S-R link,
- T_{rd} is the transmission time of data frame in R-D link,
- $(p_{dfe})_{sd}$ is the probability that data frame is lost in S-D link,
- $(p_{dfe})_{sr}$ is the probability that data frame is lost in S-R link,
- $(p_{dfe})_{rd}$ is the probability that data frame is lost in R-D link,
- $(p_{afe})_{sd}$ is the probability that ACK frame is lost in D-S link,
- $(p_{afe})_{sr}$ is the probability that ACK frame is lost in R-S link,
- $(p_{afe})_{rd}$ is the probability that ACK frame is lost in R-D link,
- ETT_{sd} is the expected transmission time for data frame in S-D link,
- ETT_{sr} is the expected transmission time for data frame in S-R link,
- ETT_{rd} is the expected transmission time for data frame in R-D link,
- $(ETT_{sd})_{COBRA}$ is the expected transmission time for data frame from S to D when R acts as a relay and COBRA MAC is used,
- $(ETT_{sd})_{TTA}$ is the expected transmission time for data frame from S to D when R acts as a relay and any of the TTA cooperative protocols is used.

The expected transmission time for COBRA MAC is given as

$$(ETT_{sd})_{COBRA} = \frac{(T_{sd} + (p_{dfe})_{sd}(1-(p_{dfe})_{sr})T_{rd})}{((1-(p_{dfe})_{sd}) + (p_{dfe})_{sd}(1-(p_{dfe})_{sr})(1-(p_{dfe})_{rd}))(1-(p_{afe})_{sd})}. \tag{1}$$

The expected transmission time for TTA cooperative protocol is given as

$$(ETT_{sd})_{TTA} = \frac{(T_{sr} + (1-(p_{dfe})_{sr})T_{rd}}{(1-(p_{dfe})_{sr})(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd})}. \tag{2}$$

Theorem 3.1: For any pair of transmission rates used on S-R and R-D link, respectively, the ETT of any TTA cooperative protocol is always greater than that of the two hop transmission from S to R and R to D, under the condition that $(1-(p_{afe})_{sd}) < \min((1-(p_{afe})_{sr}), (1-(p_{afe})_{rd})))$.

Proof: The expected transmission time of a two-hop transmission from S to R and R to D is given by

$$(ETT_{sd})_{MH} = \frac{T_{sr}}{(1-(p_{dfe})_{sr})(1-(p_{afe})_{sr})} + \frac{T_{rd}}{(1-(p_{dfe})_{rd})(1-(p_{afe})_{rd})}. \tag{3}$$

$$= \frac{(T_{sr}(1-(p_{dfe})_{rd}) + (T_{rd})(1-(p_{dfe})_{sr})\frac{(1-(p_{afe})_{sr})}{(1-(p_{afe})_{rd})}}{(1-(p_{dfe})_{sr})(1-(p_{afe})_{sr})(1-(p_{dfe})_{rd})}. \tag{4}$$

Consider the case when $(1-(p_{afe})_{rd}) > (1-(p_{afe})_{sr})$. The numerator in (4) is lower than the one in (2) as all probabilities are between 0 and 1. The denominators in both (4) and (2) have $(1-(p_{dfe})_{sr})(1-(p_{dfe})_{rd})$ in common. If $(1-(p_{afe})_{sd}) < (1-(p_{dfe})_{sr})$, then the denominator in (4) is greater than that in (2). Notes that when $(1-(p_{afe})_{sr}) > (1-(p_{afe})_{rd})$, similar conditions hold if $(1-(p_{afe})_{rd}) > (1-(p_{afe})_{sd})$. In summary,

$$if : min((1-(p_{afe})_{sr}), (1-(p_{afe})_{rd})) > (1-(p_{afe})_{sd})$$

$$then : (ETT_{sd})_{MH} < (ETT_{sd})_{TTA}$$

One case where the afore-mentioned condition holds is the one where the ACK frames are transmitted at the lowest data rate to improve their probability of success. This assumption is used in this study. Note that even when ACK frames are transmitted at different data rates, the condition holds for most cases. ■

Theorem 3.2: ETT for COBRA MAC is lower than ETT of single hop transmission from S-D if the expected forward transmission time of R-D link is smaller when compared to that of S-D link, i.e.,

$$\frac{T_{rd}}{1-(p_{dfe})_{rd}} < \frac{T_{sd}}{1-(p_{dfe})_{sd}}.$$

Proof: ETT of single hop transmission from source to destination is given by

$$(ETT_{sd})_{SH} = \frac{T_{sd}}{(1-(p_{dfe})_{sd})(1-(p_{afe})_{sd})}. \tag{5}$$

For ETT of COBRA MAC to be lower than that of single hop transmission, the difference between (5) and (1) must be greater than zero. After some algebraic simplification, this condition is expressed as:

$$\frac{T_{rd}}{1-(p_{dfe})_{rd}} < \frac{T_{sd}}{1-(p_{dfe})_{sd}} \tag{6}$$

■

In practical terms, when R is able to deliver data frame to D requiring lower expected forward transmission time than that required by S to reach D, cooperation is preferred over single hop. Note that even if collectively S-R link and R-D link do not yield a transmission time advantage, COBRA MAC may still yield lower ETT than that of a direct single hop transmission. Also note that the equation is not affected by S-R link. This implies that as long as there is a non-zero probability of reaching R from S, R may lower ETT if the above condition is met. This gives COBRA MAC a broader scope when seeking relays compared to TTA cooperative protocols.

Theorem 3.3: There exists some condition for which ETT of COBRA MAC protocol is less than ETT of two hop (multi hop) transmission with R being used as intermediate node.

Proof: It should be noted that for COBRA MAC, $T_{sd} = T_{sr}$. With this assumption, after some algebraic simplification, ETT for COBRA MAC can be rewritten as

$$= \frac{ETT_{sr}(1-(p_{afe})_{sr}) + T_{rd}(p_{dfe})_{sd}}{\frac{ETT_{sr}(1-(p_{afe})_{sr})}{ETT_{sd}} + (p_{dfe})_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd})}.$$

$$= \frac{(ETT_{sr}(1-(p_{afe})_{sr}) + T_{rd}(p_{dfe})_{sd})ETT_{sd}}{ETT_{sr}(1-(p_{afe})_{sr}) + ETT_{sd}((p_{dfe})_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd}))}. \tag{7}$$

Now, ETT when R is used as intermediate node to reach D is given by:

$$(ETT_{sd})_{MH} = ETT_{sr} + ETT_{rd}. \tag{8}$$

$(ETT_{sd})_{COBRA}$ is lower than that of multi hop (R as intermediate node) when

$$\frac{(ETT_{sr}(1-(p_{afe})_{sr}) + T_{rd}(p_{dfe})_{sd})ETT_{sd}}{ETT_{sr}(1-(p_{afe})_{sr}) + ETT_{sd}((p_{dfe})_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd}))} < ETT_{sr} + ETT_{rd}.$$

$$\frac{ETT_{sd}}{ETT_{sr}+ETTrd}(ETT_{sr}(1-(p_{afe})_{sr})+T_{rd}(p_{dfe})_{sd}) < ETT_{sr}(1-(p_{afe})_{sr})+ETT_{sd}((p_{dfe})_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd})) \tag{9}$$

If (9) is met, $(ETT_{sd})_{COBRA}$ is lower than ETT of two hop transmission. To prove that this condition can be met, consider the case where the following condition holds,

$$ETT_{sd} < ETT_{sr} + ETT_{rd}. \tag{10}$$

The fraction on the left hand side of (9) becomes less than one. In such a case it can be shown that $(ETT_{sd})_{COBRA}$ is less than ETT of multi hop when the following additional condition is met:

$$ETT_{sr}(1-(p_{afe})_{sr}) + T_{rd}(p_{dfe})_{sd} < ETT_{sr}(1-(p_{afe})_{sr}) + ETT_{sd}((p_{dfe})_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd}))$$

$$T_{rd} < ETT_{sd}(1-(p_{dfe})_{rd})(1-(p_{afe})_{sd})$$

$$\frac{T_{rd}}{(1-(p_{dfe})_{rd})} < ETT_{sd}(1-(p_{afe})_{sd})$$

$$ETT_{rd}(1-(p_{afe})_{rd}) < ETT_{sd}(1-(p_{afe})_{sd}). \tag{11}$$

An example of a scenerio where both conditions (10) and (11) are met is when R-D distance is less than S-R distance, which in turn is less than S-D distance[1]. For instance, in a line topology where all nodes are along a line, R is on one side of D, S is on the opposite side of D, and R is closer to D than S is. Thus if both (10) and (11) are met, COBRA MAC is preferred over multi hop transmission using R as intermediate node. Such conditions include those where relay does not provide a transmission time advantage. ■

In summary, though any of the link layer cooperative protocols can reduce ETT of a single hop link, only some of these protocols may be able to reduce ETT when used in conjunction with ETT based routing protocols in multi hop networks. COBRA MAC is one of such cooperative protocols.

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[1] It is assumed that transmission error rate is inversely proportional to distance.

IV. ETT - COBRA

It is understood that the cooperative link layer protocol can help reduce the expected transmission time of a frame. If the network layer is unaware of the underlying cooperative link layer protocol, it uses the expected transmission time achieved without the use of relay to establish end to end route. However the link layer, being cooperative takes advantage of neighboring nodes which can act as potential relays to reduce the expected transmission time of a packet to its next hop. It is to be noted that the network layer shares the infomation about the link quality to its link layer. The link layer then computes the CETT achieved by using each neighboring node as relay. The value of CETT is computed as follows

$$CETT = \frac{(T_{sd} + (p_{dfe})_{sd}(1-(p_{dfe})_{sr})T_{rd})\frac{1}{(1-(p_{afe})_{sd})}}{((1-(p_{dfe})_{sd}) + (p_{dfe})_{sd}(1-(p_{dfe})_{sr})(1-(p_{dfe})_{rd}))}. \tag{12}$$

The rate selection used in the compution of CETT is described in section V. The neighboring node which offers the minimum of CETT is chosen as the relay node.

V. CETT - CROSS LAYER ROUTING METRIC

The previous section proved that COBRA-MAC cooperative protocol has the potential to improve performance in multi hop networks. However, in order to be able to take full advantage of such potential improvements, an adequate metric to be used by the routing protocol must be defined. ETT used as a routing metric has been shown to offer improved performance in terms of throughput in IEEE 802.11 networks [7] over the simpler hop count.

This section extends the definition of ETT to account for cooperating protocols at the link layer. The proposed metric is termed cooperative ETT, or CETT. Given the source and destination of the link, the relay, and the transmission rates between source-destination and relay-destination, the value of CETT is computed as shown is 12.

When running the routing protocol, for each link (node pair) in the network, a value for the link metric is computed. For each link the following procedure is executed to compute such value. First, the value of ETT obtained assuming transmission without relay is computed. Note that the ETT value is the minimum of direct transmission and two hop transmissions, i.e., the relay node is used as the next hop. When evaluating the ETT metric, the transmission rate must be chosen. The transmission rate is chosen by exaustive search over all possible rates and choosing the one that is estimated to give the minimum ETT value.

Then, all potential relay candidates are considered for the link. The relay candidate that yields the minimum CETT is selected. When computing CETT for each relay candidate both transmission rate between source and relay[2], and transmission rate between the relay and destination, must be carefully chosen. The rates are computed using the following iterative procedure:

- The transmission rate for the source-relay link is temporarely chosen to be the one that minimizes the value of ETT of the source-relay link.
- The transmission rate for the relay-destination link is the one that minimizes the value of CETT (exaustive search over the rate options) as defined in (12) and accounting for the source-relay rate computed in the previous step.
- With the relay-destination rate obtained, the choice of source-relay rate is revisited by trying to further minimize CETT (12) while searching over the rate options for source-relay.

The obtained values of ETT and CETT are then compared againt each other and the better of the two is chosen as the final link metric. If ETT is chosen, cooperation is not invoked over the link. If CETT is chosen, cooperation is used when transmitting data frames over the link. Note that side products of the CETT calculation are the relay identity, the transmission rate between source and destination, and the transmission rate between relay and destination.

A. Case Study: Implementation of OLSR Based on CETT

OLSR is a popular table driven routing protocol, in which each node broadcasts both periodic hello messages and topology control messages to proactively find routes to all reachable destinations [5], [8]. To account for ETT (and CETT) metric in OLSR, link quality extensions have been introduced [9]. Using these extensions, hello messages and topology control messages are augmented with the link quality information of all neighboring nodes.

When ETT-COBRA is used, the link layer uses the link quality information about the neighboring nodes provided by OLSR, to check whether one of them could improve the expected transmision time when acting as a relay for a particular next hop node. If one such node is found, it is used as a relay.

In order to incorporate CETT, the OLSR protocol is modified to exchange CETT values (as opposed to ETT values) between neighboring nodes using its topology control messages, devised to advertise link quality information. To minimize the required changes to the protocol definition as in [8], no additional information, other than the value of the link metric, i.e., the best between ETT and CETT, is added to hello and topology control messages. Notice that the value of the link metric alone does not uniquely identify the relay, nor it identifies whether a relay will be chosen. As a result, whether to use a relay, and, if so, the

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[2] Notice that the source-relay, and source-destination rates must be the same.

TABLE I

PARAMETERS USED IN SIMULATION

Path Loss Exponent β = 4	Fading is Flat Rayleigh
Average Transmitter Power = 100 mW	PHY Header = 192 bits
SIFS = 10 μs	RIFS = 30 μs
DIFS = 50 μs	Slot Time = 20 μs
Vulnerable Period = 20 μs	Max Retrans. Attempts = 6
Frame Size = 1023 bytes	CWmin = 31 slots
CWmax = 255 slots	MAC Header = 34 bytes
MAC ACK = 14 bytes	Sensitivity = -107 dBm

relay identity must both be memorized in the routing table at the node. The protocol does require to advertise the relay identity to neighboring nodes. When a data frame is passed on to link layer for transmission, apart from the next hop information, the node must also retrieve the identity of the relay node from the routing table. The relay address is transmitted in the frame header along with the one hop destination address, to activate the correct relay on that specific frame transmission [3].

VI. RESULTS

This section presents some details about the simulation environment and then results obtained to demonstrate the impact of the proposed solution.

A. Simulation Setup

The simulator used is a custom C++ simulator validated against the analytical model presented in [10]. OLSR is used as the underlying routing protocol when comparing ETT and CETT routing metrics leading to OLSR-ETT and OLSR-CETT variants. Implementation of OLSR routing protocol closely matches the specifications in [8]. To account for the ETT metrics, both cooperative and non-cooperative, link quality extensions to OLSR are included [9]. Control packets are given priority over data packets at the internet protocol (IP) layer. In OLSR, packets that do not have a next hop towards the destination are buffered for a fixed time equal to 6 s (three hello messages or one TC message). If a route is not found after 6 s, packets are discarded at the IP layer. Transit packets are given preference over the node's own packets. The parameters used in IEEE 802.11 and cooperative MAC for simulation are tabulated in Table I.

The channel is assumed to have a flat Rayleigh fading that remains constant for the duration of a data frame. The channel model is described in detail in [11]. The sensing threshold is set to -107 dBm. Whenever a node senses a power level that is higher than -107 dBm, it assumes the channel to be busy. Spatial reuse is possible because of the finite sensitivity range value[3].

B. Simulation Results

This section presents an assessment of the impact of the use of cooperative protocols in multi-hop networks, in conjunction with the use of the CETT metric for the routing protocol. Performance simulation results are presented comparing the performance of proposed solution (OLSR-CETT) to a system based on IEEE 802.11 link layer protocols for multi-hop networks where the routing metric is ETT (OLSR-ETT).

A linear topology is considered with an internode distance of 20 m is considered first. The source and destination are chosen to be the nodes that are at the extremes of the line. The distance between the source and destination is varied from 120 m to 360 m by increasing the number of intermediate nodes. Fig. 2 shows the saturation throughput obtained for various end-to-end distances. OLSR-ETT converges to a route with 40 m hops. It is to be noted that the expected transmission time to a node 40 m away with a node 20 m away as the relay is lower than that of the expected transmission time to a node 40 m away without the relay. ETT-COBRA uses this fact to chose the 20 m node as a relay for its transmissions.

On the other hand, OLSR-CETT tries to converge to 60 m hops to reach the destination while using the node at 40 m as the relay for each link. Note that, although nodes are static, routes might change due to the fact that OLSR control messages might be lost. Clearly, the cumulative expected transmission time of the CETT chosen path is better than the plain ETT path. The value of the sum of ETTs for a 40 m and 20 m transmissions is larger than the value of CETT of a 60 m transmission with relay at 40 m. OLSR-ETT is then forced to use the node 40 m away as next-hop in its transmission. OLSR-CETT shows that there is gain by using adjoining nodes as relay rather than as a next hop and thus helps improve the saturated throughput by 20 %. Fig. 3 shows the the average cumulative transmission time obtained, i.e., the value of the sum of the link metric of all the links along the shortest path.Two set of curves are presented: analytical refers to the shortest path calculated offline,

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[3] -107 dBm sensing range with a transmitted power of 100 mW correspond to about 150 m in a nonfading channel where the path loss exponent β is 4.

simulation refers to the average of the sum of the link metrics, averaged over all packet transmissions. Since OLSR may not always converge to the optimal path simulation results show an increase in average cumulative transmission time. It could be seen that ETT-COBRA and CETT reduces the cumulative expected transmission time.

Next the inter node distance is increased to 30 m. Fig. 4 shows the saturation throughput obtained for various end-to-end distances. OLSR-ETT converges to a route with 30 m hops. Since there are no nodes that are between a node and its next hop and no node closer to the destination that itself on the other side of destination, the ETT-COBRA cannot find any relay to be used in this scenerio. Hence it performs exactly like OLSR-ETT. On the other hand, OLSR-CETT tries to converge to 60 m hops to reach the destination while using the node at the center as the relay for each link. Note that, although nodes are static, routes might change due to the fact that OLSR control messages might be lost. Clearly, the cumulative expected transmission time of the CETT chosen path is better than the plain ETT path. The value of the sum of ETTs for two 30 m transmissions is larger than the value of CETT of a 60 m transmission with relay at 30 m. Also, the value of the sum of ETTs for two 30 m transmissions is smaller than the value of ETT of a single hop transmission of 60 m. OLSR-ETT is then forced to use adjoining nodes as next-hop in its transmission. OLSR-CETT shows that there is gain by using adjoining nodes as relay rather than as a next hop and thus helps improve the saturated throughput by 20 %. Fig. 5 shows the the average cumulative transmission time obtained. Since ETT-COBRA is this scenerio behaves like ETT, the cumulative expected transmission time observed by it will be the same as that ETT, hence not reported in the figure.

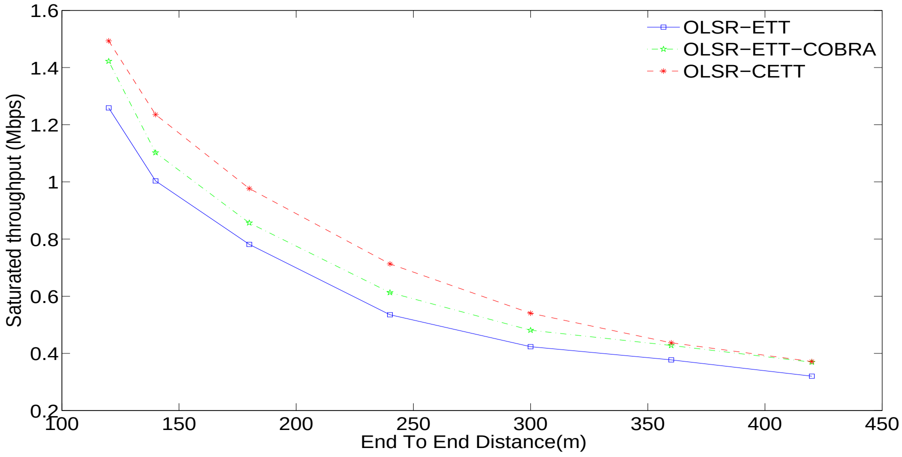

Fig. 2. Saturation throughput vs. end-to-end distance, linear topology, inter-node distance is 20 m.

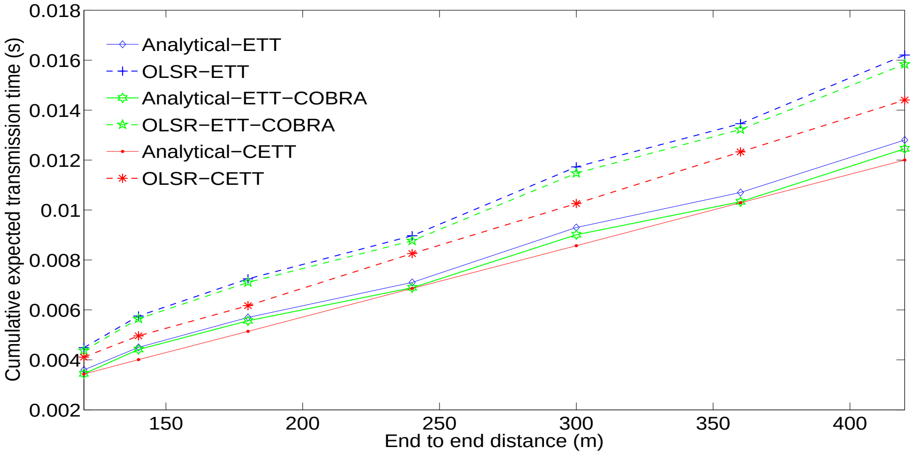

Fig. 3. Average cumulative transmission time vs. end-to-end distance, linear topology, inter-node distance is 20 m.

Next, a 5×5 grid of nodes is considered, as shown in Fig. 6. Fig. 7 shows the plot of the saturation throughput against the internode distance along the row and column of the grid when one source destination pair along the diagnal is considered.

The plot shows throughput gains as high as 50 %. OLSR-ETT chooses to go through the nodes along the diagonal. OLSR-CETT chooses the same path but can exploit the nodes around it as relays thus reducing the ETT and increasing the throughput.

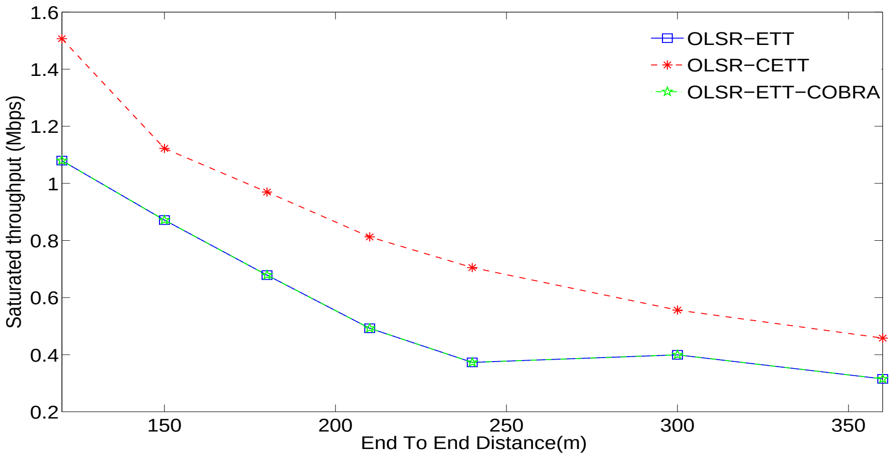

Fig. 4. Saturation throughput vs. end-to-end distance, linear topology, inter-node distance is 30 m.

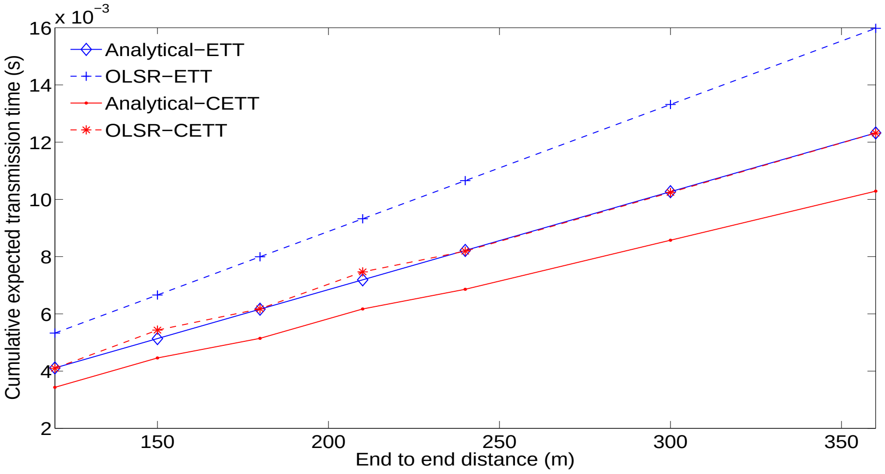

Fig. 5. Average cumulative transmission time vs. end-to-end distance, linear topology, inter-node distance is 30 m.

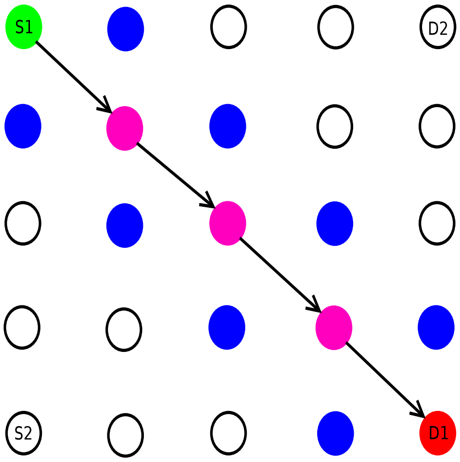

Fig. 6. A regular grid topology with 5×5 nodes.

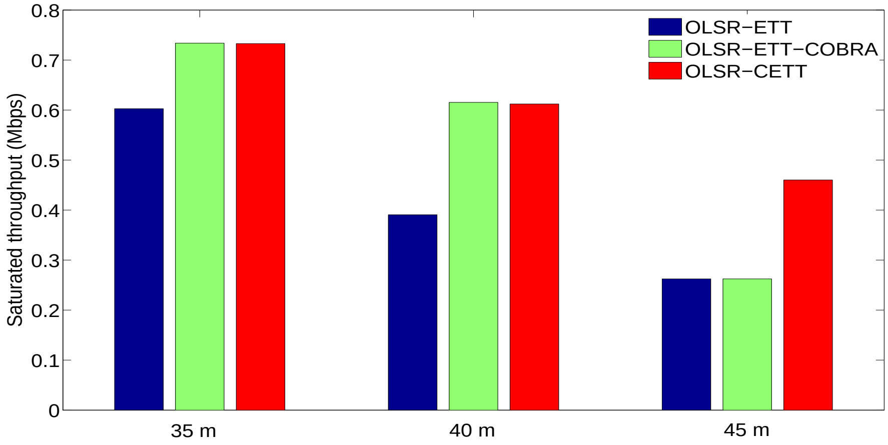

Fig. 7. A regular grid topology with 5×5 nodes: one source destination pair : saturation throughput

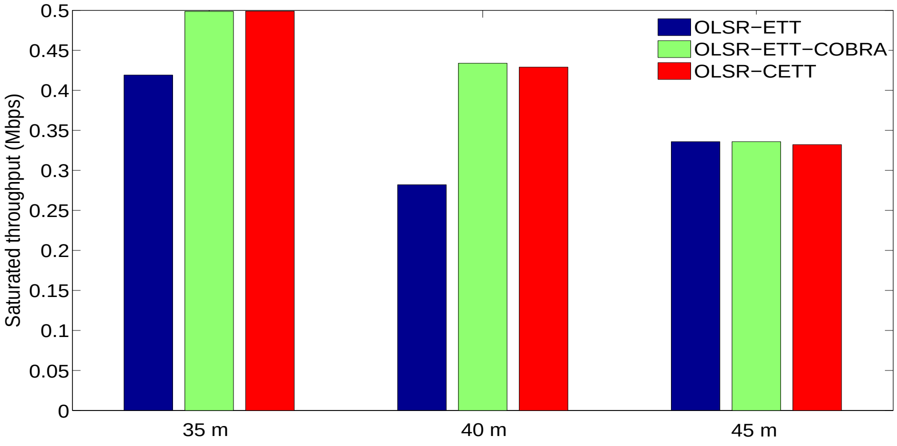

Fig. 8. A regular grid topology with 5×5 nodes: two source destination pair : saturation throughput

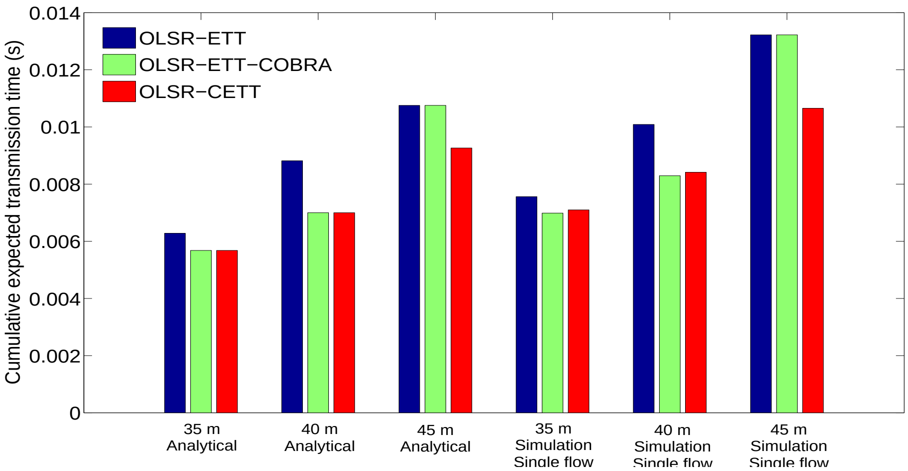

Fig. 9. A regular grid topology with 5×5 nodes: average transmission time.

When the inter node distance along the rows and colums is 45 m, the OLSR-ETT converges to 8 hops of 45 m. However OLSR-CETT still uses the diagnal nodes with the nodes on either side as relay. Thus in this case a reduction in number of hops and use of relay for each such hop enables it to perform much better than OLSR-ETT. Next two flows is considered along both the diagnals. Fig. 8 shows the plot of the saturation throughput against the internode distance along the row and column of the grid. The increase in source causes collissions resulting in decreased throughput. However at 45 m, OLSR-ETT converges to a path which runs across the column then the top row for one source and along the bottom row for another source. Thus four hops along one path is out of sensing region of the other path. Hence this results in a increased throughput when compared to a single source case.

It can be observed that under this condition OLSR-CETT provides 50 % gain in throughput consistent to the single flow case discussed previously. Thanks to the design of COBRA MAC, relays quickly retransmit the frame instead of performing a rigorous channel access procedure.

Fig. 9 shows the cumulative transmission time. Since the best route is the similar for the two flows, the optimum average cumulative metric computed by the analytical equations is the same as that for a single flow and hence is reported as a single value. Simulations results also show that on average the flows need almost the same cumulative expected transmission time. When the internode distance is 45 m, ETT with coop has the same route as ETT. However, there are no potential relays to use. In other words, the expected transmission time with relay is higher comapared to the case without the relay.

The regular topologies help understand the difference between the use of a node as a relay node as against an intermediate node. It should be noted that scenarios exist for which OLSR-CETT may not find a suitable relay and hence resort to non cooperative operation on some links.

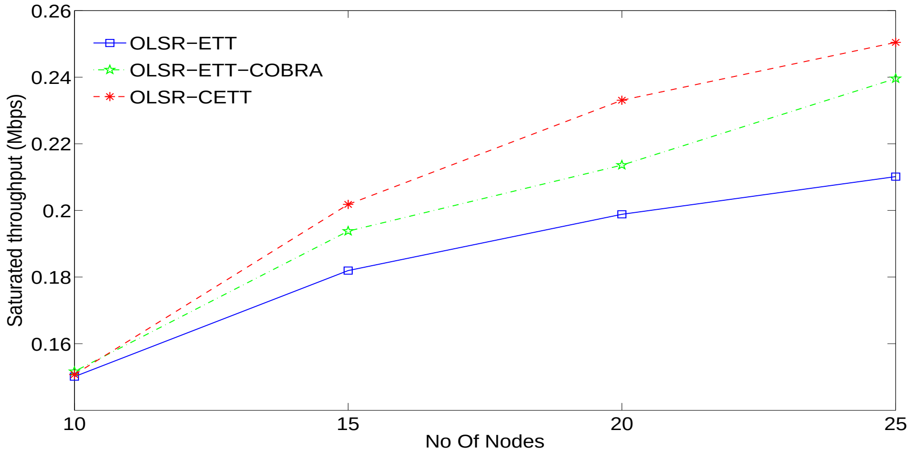

Fig. 10. Saturation throughput vs. number of nodes, random node positions, square area, 212 m X 212 m, single flow

In order to understand this effect, random topologies are considered next. A square area of size 212 m × 212 m is considered. The source is fixed to be a node at the bottom left and destination is fixed at the top right position thereby forcing the end-to-end distance between the source and destination to be 300 m. Nodes are placed uniformly in the square area. Each point in the curves is an average of 20 instances with each instance running to 250 s of simulation time. Fig. 10 shows the plot of the saturation throughput against the number of nodes in the square area. It can be observed that when only 8 nodes (apart from source and destination) are present, the network is very sparse and hence nodes that can act as potential relays to decrease the expected transmission time are infrequently available. Hence OLSR-CETT, ETT-COBRA and OLSR-ETT perform in a similar manner. However as the number of nodes is increased, they are able to find better routes to the destination. Thus an increase in throughput is seen. OLSR-CETT and ETT-COBRA takes advantage of the increased availability of potential relays and thus reduces the expected transmission time. OLSR-CETT provides throughput gains as high as 10 %.

Next, an additional flow is introduced by placing a source on the top left corner and its destination at the bottom right corner. Fig. 11 shows the saturation throughput across the network when nodes placed randomly. These two contending flows cause collisions among themselves thereby decreasing the overall throughput. Fig. 12 shows the cumulative transmission obtained for a single flow case. As explained earlier, on average this value will be similar to the one for the two flow case.

Last, a square of size 400 m × 400 m is considered. Again, nodes are placed according to a uniform distribution. Five Nodes are picked at random and are chosen as sources. Each source uniformly picks a destination for each frame transmission. Each point in the plot is an average of 40 independent instances with each instance corresponding to 250 secs of simulation time. Fig. 13 shows the average saturation throughput obtained across the number of nodes. It can be observed that when the number of nodes is doubled the number of contending flows is also doubled. This leads to increased collisions in the network causing the saturation throughput to decrease. However it can be seen that OLSR-CETT and ETT-COBRA are able to provide

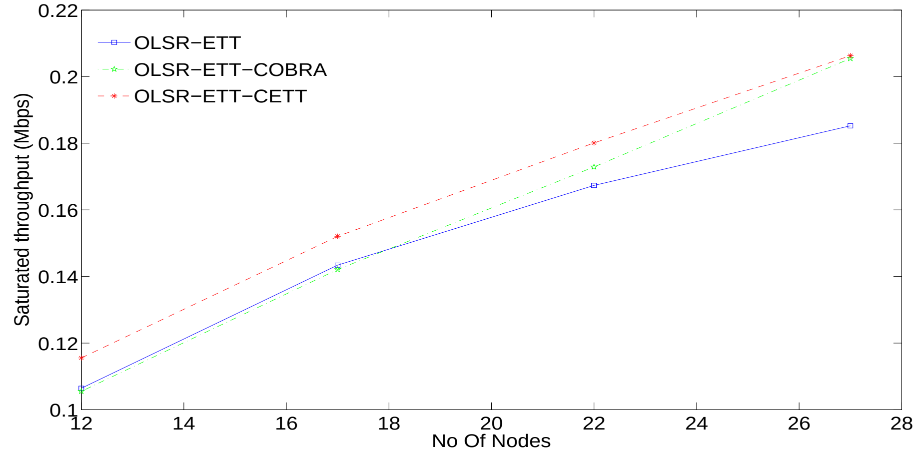

Fig. 11. Saturation throughput vs. number of nodes, random node positions, square area, 212 m×212 m, two flows

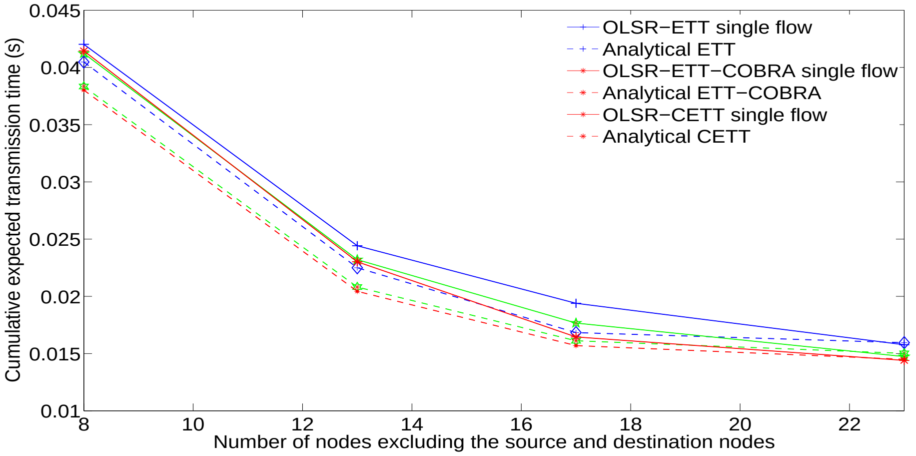

Fig. 12. Average cumulative transmission time vs. number of nodes, random node positions, square area, 212 m×212 m, two flows

a higher throughput as they decreases the expected transmission time.

Fig. 14 shows the average cumulative transmission time. It can be observed than an increase in number of nodes coupled with an increase in number of flows, increases the chances of control frame losses. This leads to a larger number of packets following sub-optimal paths and hence simulation results shows an increased cumulative transmission time.

VII. SUMMARY

The study presented in this paper established that not all cooperative link layer protocols are suited to operate in multi-hop wireless networks. It further introduced a routing metric, termed cooperative expected transmission time (CETT), which may be adopted in multi-hop networks when using a suitable cooperative link layer protocol. CETT is defined to estimate the frame transmission time required over one single hop, while accounting for the presence of potential relay nodes within reach. If adopted as a routing metric, CETT allows routing protocols to jointly optimize both the end-to-end route computation and relay selection for every link along the route.

The CETT metric was applied to OLSR protocol, to illustrate a possible implementation of the same and measure expected performance gains by means of simulation. Tangible reduction of cumulative transmission time and consequent increase of overall network throughput were noted, up to 50%, when compared to conventional routing based on the ETT metric. Also, joint optimization of routes and relays seems a better choice than sequentially finding routes and relays. These gains were noted to vary greatly, depending on the topology (node distribution) of the multi-hop network.

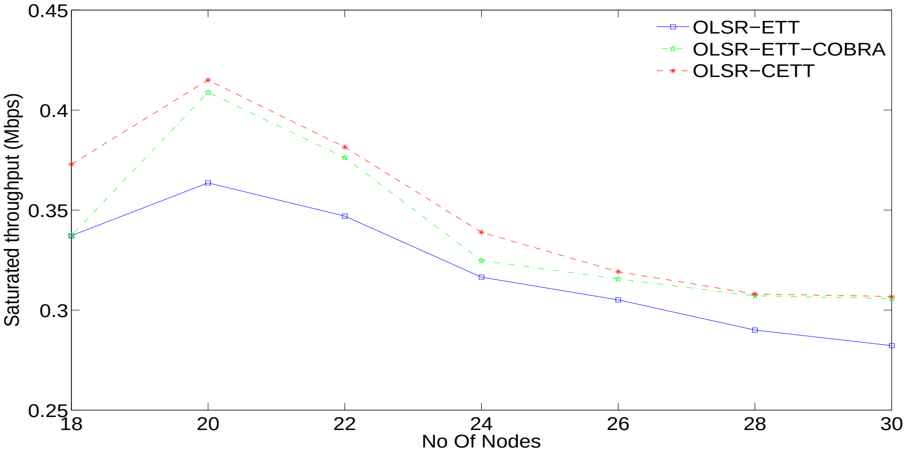

Fig. 13. Average saturation throughput vs. number of nodes, random node positions, square area 400 m×400 m, five sources

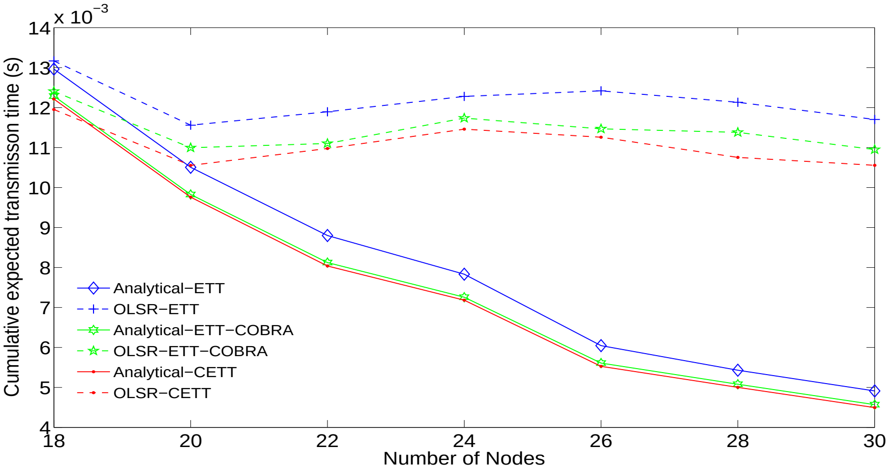

Fig. 14. Average expected cumulative transmission time vs. number of nodes, random node positions, square area 400 m×400 m, five sources

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