Network Layer Connectivity Awareness with Application to Investigate the OLSR Protocol in Tactical MANETs

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NETWORK LAYER CONNECTIVITY AWARENESS WITH APPLICATION TO INVESTIGATE THE OLSR PROTOCOL IN TACTICAL MANETS

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ABSTRACT

We propose a new local networking metric, the network layer connectivity awareness (NLCA), to dynamically characterize the connectivity status at the network layer of mobile ad hoc networks (MANETs). The NLCA is a local view of routable destinations provided by a designated routing protocol, which may differ from the real-time physical layer connectivity (PHYCON), defined as destinations that can be reached by local nodes via (multi-hop) radio links. Such discrepancy can cause packet delivery failure because a route may no longer be available at physical layer. We present a simulation method to obtain the real-time PHYCON using the breadth-first search algorithm. We apply the NCLA metric to the optimized link state routing (OLSR) protocol in scenarios simulating tactical MANETs, and compare the resulting NLCA with the underlying PHYCON, illustrating the two measurements vary and differ under mobility. The proposed NLCA and investigation technique provide a method for routing performance analysis.

1 INTRODUCTION

Mobile ad hoc networks (MANETs) provide a promising technology for military operations, especially in tactical scenarios where communication infrastructures may not exist. The self-forming and self-organizing characteristics of MANETs enable the rapid setup of a dynamic wireless network in complex terrains. One benefit of MANET technology comes from effective routing to achieve data delivery across multi-hop routes. One popular protocol that performs such multi-hop delivery proactively is the optimized link state routing (OLSR) protocol (Clausen and Pacquet 2003).

In OLSR, a routing table is continuously calculated using neighbor and topology information obtained by the neighbor discovery and topology control processes, via HELLO and TC messages respectively, and a shortest path routing algorithm. The routing table consists of a set of destinations and the next hop for the destination, plus other desired metrics such as the cost (number of hops to the destination). We call these destinations ***routable***, i.e., there exists a route to the destination provided by the routing table. In general, at any given time, a MANET node is aware of the destinations in the network to which it can route a data packet, based on the routing knowledge at the network layer. We refer to the measure of connectivity status from the network layer's perspective as the network layer connectivity awareness (NLCA), represented by the set of routable destinations. The NLCA is measured locally and characterizes the capability to send data packets to the destinations by the local node. The NLCA may not reflect the network topology and connectivity at the physical layer (PHY) in real-time, which is particularly true in case of significant topology changes due to mobility.

The physical layer connectivity (hereafter in this paper referred to as PHY connectivity, or abbreviated as PHYCON) has been an active research topic in mobile wireless networks with extensive results in the literature, for examples see the early work in Miller and Kellerher (1992), and a survey in Li (2004) and the references therein. The PHYCON is mainly determined by the radio ranges and the distance between nodes in a wireless network, and can be affected by many factors, such as signal degradation/loss, interferences, noise, and terrain conditions; as such the "connectedness" is generally not a binary value, especially at the edge of the transmission range. Rosen, Stine and Weiland (2006) introduced the propagation maps to specify network connectivity for node state routing (NSR) protocol, with a study on effective algorithms for generating the propagation maps. However, in this work we simply consider the PHYCON based on the radio range and relative node locations. We say two nodes are immediate neighbors if the nodes fall within the radio range. Taking into account multi-link relays, a node can send signal to remote nodes that are not its immediate neighbors. We call those nodes physically connected, or ***reachable*** from the local node. For a given node, finding all reachable nodes in the MANET can be achieved by a graph traversing algorithm. We shall use the well-known breadth-first search (BFS) (Moore 1959) to calculate the reachable node set for a node at any desired time.

The OLSR routing process relies on the periodic HELLO and TC message exchanges for multi-point relay (MPR) calculation and topology discovery, based on which the routing table is updated. At the time of routing table calculation, the neighbor and topology information may already be obsolete since the nodes are mobile. This is the main reason that the NLCA and PHYCON may not be in agreement in wireless mobile networks. If a destination is deemed routable at the routing layer, but actually not reachable at physical layer, the data packet cannot be delivered to the (multi-hop) destination based on the routing information, which in turn will reduce the packet delivery radio (PDR). This observation motivates us to examine the discrepancy of the connectivity measurements between what is seen at the network layer and the underlying physical reality.

We perform our investigation and analysis using the network simulation tool EXata (SNT 2008-2017). The EXata simulation platform provides a complete software library based on the open systems interconnection (OSI) model. Specifically, it features modelling and simulation of wireless networks at physical layer, which is reasonably realistic in quantifying the real-world connectivity. In addition, the centralized simulator engine maintains real-time knowledge of the dynamic network topology, a key feature required for deriving the PHYCON using the BFS algorithm. We have enhanced the EXata software to calculate the NLCA and the PHYCON at each node, and continuously collect their statistics throughout the entire simulation session for a real-time performance analysis of the OLSR protocol.

We create two typical tactical MANET scenarios using an enhanced reference point group mobility (RPGM) model (Hong et al. 1999) to demonstrate how the NLCA can be utilized to investigate the behavior of the OLSR protocol, and evaluate factors that can affect the synchronization between the network layer connectivity and the PHY connectivity. Our results demonstrate that the NLCA is indeed a useful metric in the characterization of the effectiveness and timeliness of a routing protocol, as well as in the performance analysis of tactical MANETs.

The main contribution of this work is to differentiate the connectivity status by the OSI layers (network vs. physical). With the introduction of the NLCA, we reveal the inherent issue in most MANET routing schemes: the connectivity status as seen by the network layer being out of synchronization with the physical layer reality, i.e., the discrepancies between the NLCA and PHYCON. Such discrepancies could cause packet delivery failures since the routes may no longer be available at physical layer, hence can have negative impact on conventional MANET performance metrics, such as PDR, end-to-end delays, and throughput. We exemplify our analysis technique by investigating the OLSR protocol. In the literature, the performance analysis for OLSR has been mainly focused on the factors in protocol-specific setup, topology changes, congestions, traffic volumes, etc.; see for examples Demers and Kant (2006) and Plesse et al. (2005). We believe our work is the first that investigates the OLSR protocol from the perspective of synchronization of the connectivity status between the network layer and the PHY layer.

The rest of the paper is organized as follows. In the next section we introduce the NLCA metric and the description of the PHY connectivity in mobile wireless networks. In section 3 we describe the simulation implementation and investigation method, with focus on the OLSR protocol. In section 4 we present the tactical scenarios and the simulation results with an analysis. Concluding remarks and discussions are presented in the final section.

2 THE NETWORK LAYER CONNECTIVITY AWARENESS AND THE PHYSICAL LAYER CONNECTIVITY

In this section we define the NLCA metric and describe how the PHY connectivity is calculated in our approach. Our focus in this paper is on OLSR protocol for tactical scenarios; therefore, we present the definition in a general sense for mobile ad hoc networks.

2.1 The Network Layer Connectivity Awareness

In a MANET, each node is capable of performing a routing function to find a route to deliver (unicast) application data to intended destinations. The routing function resides at the network layer in the OSI model, and maintains a local routing database. The routing database can be table-based (proactive), or generated as needed (on-demand), or a combination of the two (hybrid). Every entry in the routing database specifies a route to a routable destination, representing local node's connectivity to that destination from the network layer's perspective. Note that each entry in the routing database possesses a timestamp that corresponds to the time of the most recent update to the entry. We refer to the difference between the current time and the timestamp as the age of that entry. We further introduce a threshold, denoted by *nlca_thresh*, to qualify a routing entry as valid if the age of the entry is less than *nlca_thresh*. We define the NLCA metric as follows.

Definition. *The Network Layer Connectivity Awareness is a metric for MANET routing protocols that quantifies a local node's connectivity to its network peers from the network layer's perspective. It is represented by the set of the distinct destinations from all valid route entries in the routing database.*

We use the qualifier "distinct" in the above definition because there might be multiple entries, i.e., routes, for the same destination in the local routing database, depending on the protocol and the policy/metrics considered in the routing algorithm. For the NLCA, we count a destination with multiple routes just once. We also use the *nlca_thresh* to exclude stale (invalid) entries in the routing database. The NLCA is represented by a set of routable destinations, hereafter denoted by ***rtbSet***. The NLCA as defined above may be used in two forms: 1) the number of distinct destinations of NLCA, which is the size of the routable node set, denoted by **|*rtbSet*|** using the set cardinality notation; 2) the set of destination nodes, which is represented by listing all elements of ***rtbSet***. Both scalar and set forms can be useful depending on the use cases, however the set form is often more descriptive when comparing with the PHY connectivity, as we will see in the subsequent sections. Note that NLCA is node-specific, we use the notation ***rtbSet(n)*** to specify the metric for designated node *n* when needed.

The NLCA also indicates a local node's capability to deliver unicast application data to a desired destination, which is an important performance factor in MANET routing. The NLCA is closely related to conventional routing metrics such as PDR and end-to-end delay in the following sense. A high NLCA at a neighboring node implies that it has a high likelihood to be a relay point for its neighbors. Consequently, the collective NLCA (of all the MANET nodes) has an effect on PDR and end-to-end delay, where a high NLCA could indicate high PDR and low delay. The NLCA metric is particularly useful in MANETs because it is locally measured, whereas PDR or end-to-end delay must be measured at both source and destination. In addition, the NLCA metric is established before the actual data traffic is sent in the network, making it a helpful tool in traffic engineering.

It is a big challenge in MANET routing to keep the network topology synchronized with the physical reality. In tactical MANETs, where nodes may move frequently, the rapid changes in network topology may not be reflected in the routing function in a timely manner due to both the latency and the losses of the control messages that carry topology information. The proposed NLCA metric provides a rigorous way to measure the synchronization between the network layer view of connectivity and the PHY layer connectivity, which is further detailed in the next subsection.

2.2 The Physical Layer Connectivity and the Breadth-First Search Algorithm

The PHYCON is defined as the simple "reachability" at the physical layer, i.e., we say a remote node is physically connected to the local node if there exists a (multi-hop) link path such that the radio signal transmitted from the local node can be received by the remote node (with relaying in multi-hop case). We denote node *n*'s PHY connected (reachable) node set by ***rchSet(n)***. Between adjacent nodes, the PHY connectivity is mainly determined by transmitter/receiver's physical properties, channel conditions and data rate. For example, in the 802.11 protocol, different data rates may be used at the PHY layer: the physical layer convergence procedure (PLCP) preamble and header are normally transmitted at lower data rates (1Mb/s or 2Mb/s) to achieve a larger range, while the data packets are transmitted at much higher rates. We will give an example in section 4 to show the radio range variations at different data rates.

Although the PHYCON defined by "radio range" may not be adequate to accurately describe the wireless node reachability in real-world, for simplicity we calculate the PHYCON solely based on the distance between adjacent nodes. We call all nodes within node *n*'s radio range the adjacent node set, denoted by ***adjSet(n)***. With the knowledge of ***adjSet*** for all nodes, we use a typical graph traversal algorithm to obtain the reachable set ***rchSet*** for any node in the network. In this paper we use the BFS algorithm (Moore 1959) and outline the steps below:

```
Step1 Get real-time location of all nodes in the network
Step2 For each node n, calculate its adjacent node set adjSet(n)
Step3 For each node n, proceed with the following BDF procedure:
    BFS(n):
        Create rchSet(n), add n as the initial element
        Create a generic FIFO queue Q
        Q.enqueue(n)

        while Q is not empty:
            s = Q.dequeue()
            for each t in adjSet(s):
                if t is not in rchSet(n):
                    add t to rchSet(n)
                    Q.enqueue(t)
                if rchSet(n) contains all nodes in the network:
                    return rchSet(n)
        return rchSet(n)
```

The above procedure provides ***rchSet*** for every node in the network, which is the set representation of the PHYCON. Note that the size of ***rchSet***, **|*rchSet*|** may also be used to describe the PHYCON.

2.3 Remarks on the NLCA and the PHY Connectivity

Ideally, if the NLCA matches the PHYCON, i.e., ***rtbSet(n)*** = ***rchSet(n)*** for any node *n* at all times, one can conclude that the routing function exactly reflects the connectivity status at physical layer. Under some circumstances this can be achieved, for example in case of low mobility (quasi-static network) or long radio range such that the topology changes are not rapid. In reality, discrepancies between ***rtbSet*** and ***rchSet*** may occur frequently. Some affecting factors include:

- The topology and physical medium changes in the network due to mobility and terrain condition;
- The latency and loss of control messages on which the routing database is updated;
- The efficiency and timeliness of the routing algorithm may be low. For example, in OLSR the obsolete routing entries may persist; a hold timer is required to reset the related tables.

In a tactical MANET, the above factors can be significant, resulting in considerable differences between the network layer view of the connectivity and the physical reality. This discrepancy causes data delivery failures since the routing provides an unreachable path to the intended destination of the data packet. We submit that this cause of packet delivery failure warrants special attention in the investigation and performance analysis of tactical MANETs.

The NLCA is a local measurement that is available at individual nodes. By simply looking at the NLCA, a node in a MANET can determine how well it is connected to its peers. This insight is useful in the data forward decision-making at the local node level.

The computation of PHYCON relies on the global topological view of a MANET, since the derivation of ***rchSet*** requires locations of all nodes in the network. By the nature of a dynamic distributed network, individual nodes in a real-world MANET do not have the capability to obtain the real-time PHYCON. The simulated environments, by contrast, provide a capable platform for the performance analysis based on the measurements of the NLCA and the PHYCON since the dynamic global topology knowledge is available to be monitored on a simulator.

3 SIMULATION DESIGN AND IMPLEMENTATION ON THE SIMULATOR

In this section we describe the simulation technique for the NLCA and the PHYCON, as well as the analysis method for OLSR in the tactical scenarios. The work consists of the following components:

- Update the PHY modelling code and implement the BFS algorithm in EXata software for the calculation of the PHYCON at desired time for every node in the network;
- Update the OLSR routing code to include the calculation of the NLCA metric;
- Enhance the group mobility functionality in the wireless library for the simulation of tactical MANET scenarios; and
- Implement a process to collect performance statistics continuously throughout the simulation execution for the real-time performance analysis.

3.1 Calculation of PHY Connectivity and the NLCA for OLSR

The EXata software comes with a full implementation of the physical layer modelling for wireless communications. In program files phy_connectivity.h/cpp, the C++ class PHY_CONN_NodePositionData has been defined to provide a set of methods for the calculation of physical connectivity between a transmitter/receiver node pair. We added a new member function in this class to obtain the ***adjSet*** for every node in the network, namely the steps 1 and 2 in section 2.2 are completed by using the existing EXata functions. We created new files phy_conn_bfs.h/cpp to implement the BFS algorithm as specified in step 3 of section 2.2. Note the above functions are to be called when needed, i.e., whenever the PHYCON data is required as described in subsection 3.3 below.

The OLSR protocol has been implemented by routing_olsr-inria.h/cpp in the wireless library of EXata. The OLSR routing table consists of routing entries with the following attributes: destination, next hop, cost and outgoing interface. To calculate the NLCA metric we add a timestamp attribute to each routing entry, which keeps the time of the most recent update. At the time of NLCA calculation, we examine the routing table and list all distinct destinations with the route age less than the pre-configured *nlca_thresh*. In addition, we couple the NLCA and the PHYCON calculations at the same time for the purpose of comparison, i.e., we invoke the PHYCON function immediately prior to the NLCA computation.

3.2 Real-Time Performance Data Collection and Analysis Techniques

As per the definition above, both the NLCA and the PHYCON are time-dependent, and as such, they should be analyzed in a real-time manner. To perform the real-time analysis, in this work we implement a generic data collection function on the simulation platform that is similar to the one we used in our previous work (Li et al. 2014 and Li, Salmanian and Brown 2015). This function is invoked to calculate the PHYCON and the NLCA periodically at a configurable time interval, denoted by *log_int*. By adjusting the value of *log_int*, we investigate the behavior of the OLSR protocol using related metrics on desired time scales (granularity). The whole process involves the following steps.

- Set a configurable *log_int* for the simulation scenario, create a timer at the initialization stage of an EXata simulation session.
- At timer expiration, use procedures described in the previous subsection to obtain ***rchSet*** and ***rtbSet*** for each node.
- Output the above real-time statistics to a data file, where each line consists of node id, timestamp, and list of members in ***rchSet*** and ***rtbSet***, respectively.
- Perform a post-mortem analysis based on the resulting data file from the simulation execution.

Our primary focus in the simulation testing is on the validation of the NLCA applied in OLSR protocol, with comparison against the benchmark PHYCON. Particularly, we are interested in the real-time agreement/discrepancy between ***rtbSet*** and ***rchSet***. We use the conventional notations and the standard way of comparing two sets: the set-theoretic difference ***rtbSet – rchSet*** and ***rchSet – rtbSet***, as well as the symmetric difference (***rtbSet – rchSet***) ∪ (***rchSet – rtbSet***). The results can be presented either by listing all elements in the concerned sets, or by the size (cardinality) of the sets. In the latter case, we also evaluate the average (over the network) and maximum (node-wise) values of the size of ***rtbSet***, ***rchSet***, and their symmetric difference (symdiff), which will be referred to in section 4 as the number of routable destinations, the number of reachable destinations and the size of symdiff, respectively.

3.3 Modified Group Mobility Model for Tactical Scenarios

The modelling and simulation of mobility for MANETs has long been an active research area with plenty of results in the literature; we refer to Camp, Boleng and Davies (2002) and Treurniet (2014) for comprehensive surveys. Of particular interest is the reference point group mobility (RPGM) model (Hong et al. 1999) as it is well-suited to reflect the real-world behavior of tactical mobile networks. In the RPGM model, nodes are divided into groups, the movement of a node is the composition of two components: group and internal (within the group) mobility. In the current RPGM implementation in EXata, both group and internal mobility are modelled by random walk. To better simulate the tactical scenarios, we enhanced the RPGM algorithm in EXata such that the group mobility is controlled by pre-defined trajectories. We achieve this goal by introducing a new configuration file which defines movement of the group anchor nodes, in the form of (time, node id, location). This file is read into the program at the initialization stage, and is used to configure the mobility of each node during the course of the simulation session. We'll show two resulting node trajectories defined by this method in the next section.

4 TACTICAL MANET SCENARIOS AND SIMULATION RESULTS

We present two typical tactical scenarios in this section to demonstrate the application of the NLCA metric. We have three groups of design parameters to consider: 1) the parameters to define the RPGM mobility, such as the group sub-terrain (boundaries of the internal move within a group), the minimum and maximum group/internal speed for the random walk; 2) the OLSR protocol specific parameters such as HELLO/TC intervals and neighbor/topology table hold timers; 3) the physical layer modelling parameters that configure the radio ranges.

We use the PHY layer configuration tools in EXata to obtain desired radio ranges for each scenario. The physical layer parameter values we use in our two scenarios are summarized in Table 1 (using EXata terminology). Based on those values, we obtain the radio propagation range at different data rates by using the PHY modelling function in EXata. The resulting radio ranges are listed in Table 2.

The OLSR protocol parameters are taken from the default values in EXata, where *hello_int* = 2s, *TC_int* = 5s. The timeout value for neighbor tables and topology tables is set to 6s and 15s, respectively.

The parameters for RPGM configuration are specified for each scenario in the corresponding subsections below. The node movement trajectories for the two scenarios are depicted in Figure 1.

Table 1: Parameter values used in EXata PHY layer configuration.

Scenario	*Radio Model*	*Channel Freq. (MHz)*	*Trans. Power*	*Ant. Height*	*Ant. Efficiency*
1	Abstract	2400	10.0dBm	0.7m	0.74
2	802.11b	2437	15.0dBm	1.4m	0.50

Table 2: Radio ranges calculated by the PHY modelling function in Exata.

	Scenario 1	*Scenario 2*			
Data rate	2 Mbps	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
Radio range	85m	171m	101m	125m	99m

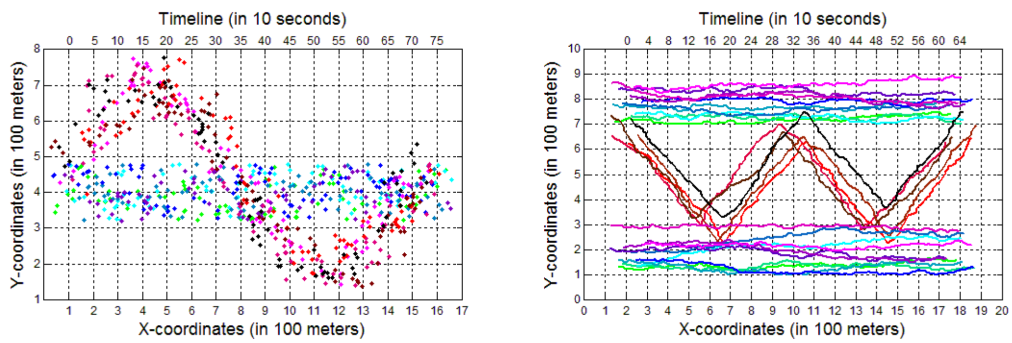

Figure 1: Node movement trajectories for Scenario 1 (the left subplot) and Scenario 2 (the right subplot).

4.1 Scenario 1: Two-Group Infantry-Paced Movements

This scenario consists of two 5-node groups (nodes 1-5 and nodes 6-10) moving in a 1700m by 800m area. The internal (nodal) and group maximum speeds are 6m/s and 3m/s, respectively. The group sub-terrain is a square area of 160m by 160m. The mobility trajectories for all 10 nodes are depicted in the left subplot of Figure 1, where nodes are identified by different colors. The total simulation time is 750 seconds. Note that in this scenario the radio range is 85m so the two groups are separated at certain times. This scenario is chosen to investigate the group separation/re-joining effects on the connectivity status. The node behavior in this scenario was studied in Li, Salmanian and Brown (2015).

In Figure 2 we depict the average (across network) and the maximum (node-wise) values of the size of ***rchSet*** and ***rtbSet***, which quantify the PHYCON measurement and the NLCA metric, respectively. We observe that the group separation/re-joining mobility pattern is clearly reflected in the figure as expected, where the PHYCON shows more variations, representing the detailed real-time changes of the physical connectivity, which have not been captured by the NLCA at the network layer. On the other hand, the curves for the NLCA are smoothed out, an indication that the network layer connectivity is not in synchronization with the physical reality as the routing protocol couldn't accurately reflect the rapid changes in real-time for this scenario.

In Figure 3(a) we plot the results for the symmetric difference, namely the discrepancy between the PHYCON and the NLCA. It is clear that the difference is fairly large: the average value can be more than 4 (half of the remote nodes). Certain nodes reached the maximum value of 9 occasionally, indicating that at those moments, ***rtbSet*** and ***rchSet*** are disjoint, i.e., remote nodes are either in ***rtbSet*** – ***rchSet*** (the node is not reachable but the routing table still has the obsolete route) or in ***rchSet*** – ***rtbSet*** (the node is reachable but the routing protocol failed to update the routing table with the route). In this extreme case, the specific node is not providing a valid route to any destination, even if the destination is reachable at the physical layer. Finally, in Figure 3(b) we combine the average values of the NLCA and PHYCON measurements, depicted in Figure 2 (a) and (b), in one diagram for better visualization. The root-mean-square-error (RMSE) between the two data sets is also presented in Figure 3(b), however we emphasize that the size of the symmetric difference is a more meaningful indicator.

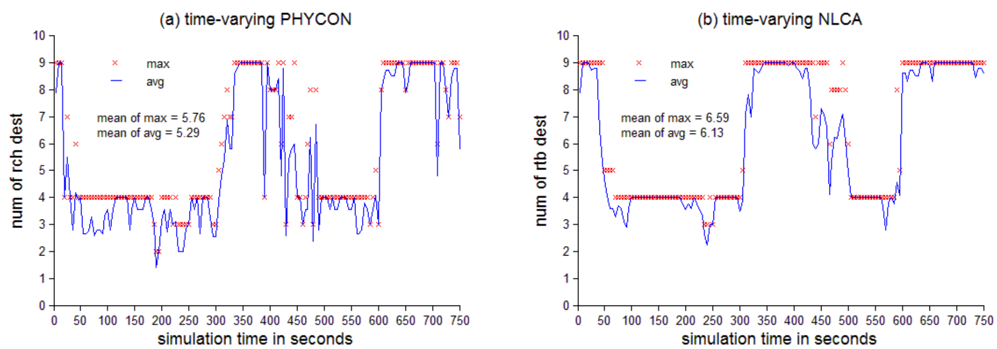

Figure 2: Scenario 1 – average and maximum values of NLCA and PHYCON at high mobility, measured by the number of routable destinations and reachable destinations, respectively.

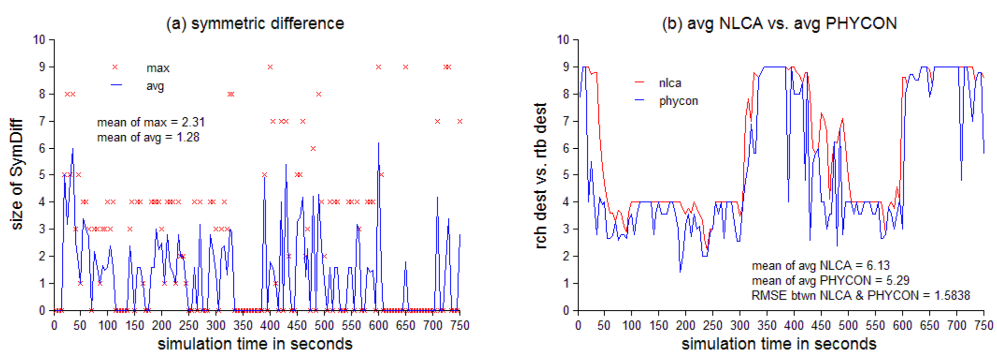

Figure 3: Scenario 1 at high mobility – average and maximum values of the size of symmetric difference between ***rtbSet*** and ***rchSet*** ; and the comparison of average NLCA against average PHYCON.

The main reason for the significant discrepancies between the PHYCON and the NLCA in Figures 2 and 3 is the rapid changes of network topology due to the fast-paced mobility. To investigate the effect of the mobility, we re-run Scenario 1 with the total simulation time doubled to 1500 seconds. The group and internal speeds are also reduced so the node movements are slowed down proportionally. The counterpart results are shown in Figures 4 and 5 with the same format as in Figures 2 and 3, respectively. We note that in this case, the NLCA and PHYCON measurements indeed agree better. We also point out that there are other means (not pursued further in this paper) to improve the synchronization between the NLCA and the PHYCON, for example, in OLSR protocol we could use smaller HELLO and TC intervals to carry the control messages more frequently across the network (at the cost of throughput).

For the purpose of more detailed comparison, we have also re-run Scenario 1 with the simulation time set to 1000 seconds and 1200 seconds, respectively. The resulting diagrams are omitted here; instead, we list the statistical characteristics in Table 3. From the table we see the trend that when the mobility slows, the discrepancies between the NLCA and PHYCON, represented by the size of the symmetric difference (referred to as symdiff in the table), also decreases. The similar trend of decreases is observed for the RMSE between the number of routable destinations and the number of reachable destinations.

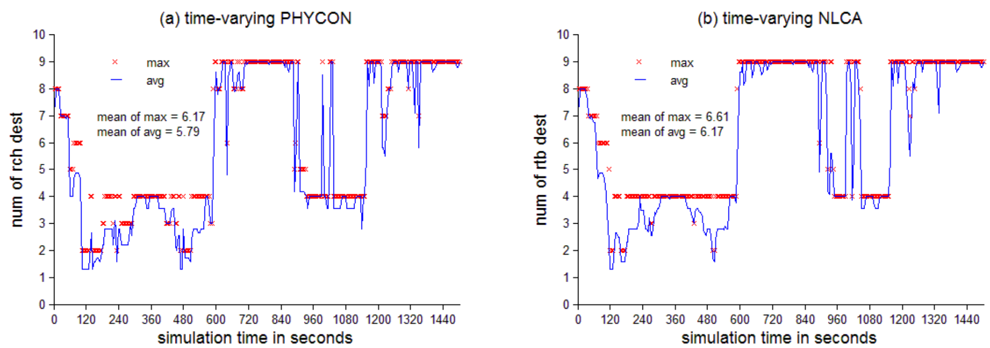

Figure 4: Scenario 1 – average and maximum values of NLCA and PHYCON at low mobility, measured by the number of routable destinations and reachable destinations, respectively.

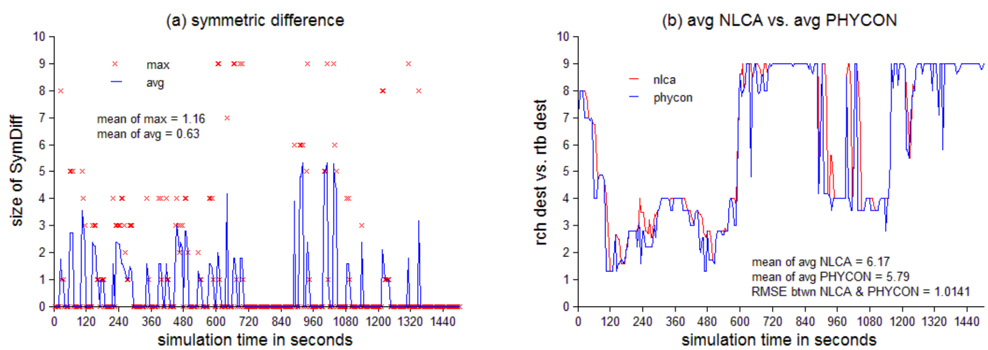

Figure 5: Scenario 1 at low mobility – average and maximum values of the size of symmetric difference between ***rtbSet*** and ***rchSet*** ; and the comparison of average NLCA against average PHYCON .

Table 3: Summary of the statistics of various mobility cases in Scenario 1.

simulation time	***avg/max of |rchSet|***	***avg/ max of |rtbSet|***	***avg/max of |symdiff|***	***RMSE of |rtbSet| & |rchSet|***
750s	5.29 / 5.76	6.13 / 6.59	1.28 / 2.31	1.5838
1000s	5.13 / 5.70	5.82 / 6.50	1.09 / 2.03	1.3234
1200s	6.00 / 6.46	6.56 / 7.05	0.91 / 1.79	1.2570
1500s	5.79 / 6.17	6.17 / 6.61	0.63 / 1.16	1.0141

4.2 Scenario 2: Three Groups with Heterogeneous Mobility

This scenario is set on a 2000m by 1000m terrain, and consists of two 10-node groups (group 1 and 3) moving in parallel at a low speed and one 5-node group (group 2) moving at a high speed in a saw-toothed pattern between groups 1 and 3. The related RPGM parameters are summarized in Table 4 below. The resulting node trajectories are depicted in Figure 1 (the right subplot). The total simulation time is set to 640 seconds. We note that the radio propagation range for data packets is in a 99m to 171m range as shown in Table 2 (the long range of 171m at 1Mbps is used for the physical layer control packets, while the shorter ranges are used by data transfer at higher rates). As a result, one group is completely separated from the other two in some time segments, as shown in the right subplot of Figure 1.

Table 4: Scenario 2 RPGM parameter values.

group	*group sub-terrain*	*min/max internal speed (m/s)*	*min/max group speed (m/s)*
1 & 3	160m by 200m	0 / 5	0 / 3
2	160m by 160m	0 / 15	2 / 12

The simulation results are presented in Figures 6 and 7 below using the same format as in Scenario 1. We observe that for this scenario the NLCA and PHYCON measurements agree fairly well, with the exceptions at the time segments around 75s and 380s. The differences between the NLCA and the PHYCON in those time segments are not easy to anticipate from the trajectory diagram, while our analysis technique can be used to help revealing those subtle details of the connectivity status. On the other hand, Scenario 2 presents a case where the good match between the NLCA and the PHYCON implies that the underlying routing protocol (OLSR) provides reliable routes for the scenario. We attribute this to two main factors: 1) the topology changes are not rapid under the given mobility pattern; 2) the radio ranges are relatively large, hence the occurrences of dis-connectivity are not very frequent.

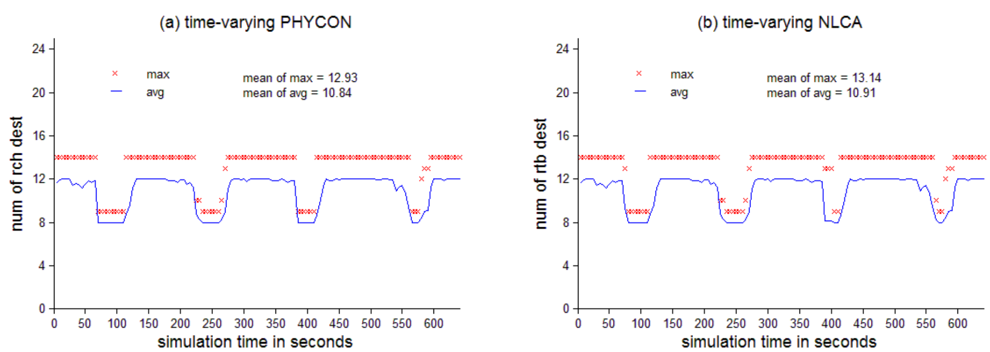

Figure 6: Scenario 2 – average and maximum values of NLCA and PHYCON, measured by the number of routable destinations and reachable destinations, respectively.

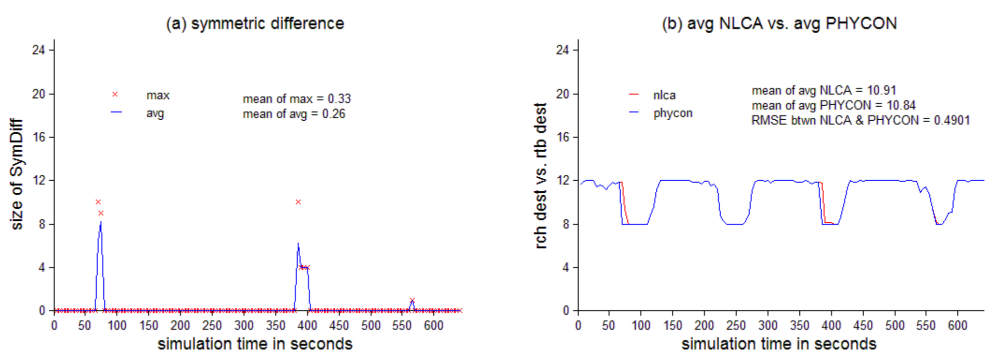

Figure 7: Scenario 2 – average and maximum values of the size of symmetric difference between ***rtbSet*** and ***rchSet*** ; and the comparison of average NLCA against average PHYCON .

In the two scenarios discussed in this section, node movements are in a well-grouped pattern. The NLCA and the PHYCON measurements at individual node behave similarly within a group, so we could present the results by the averaged value. The node-wise maximum values in the diagrams are used to show the deviations of the NLCA and PHYCON measurements among mobile nodes. For more complicated tactical MANET scenarios, with or without well-formed group mobility patterns, one can expect that investigating the NLCA and the PHYCON behavior at designated nodes could be more useful in revealing the characteristics of the network connectivity, as well as in the performance analysis of the routing protocol.

5 DISCUSSION AND CONCLUDING REMARKS

We introduced the NLCA metric for MANET routing protocols and demonstrated its application to the OLSR protocol. The new NLCA metric was compared against the baseline PHY connectivity, which was calculated by the breadth-first search (BFS) algorithm implemented on the EXata simulator. The simulation results for the two tactical MANET scenarios show that the NLCA can be locally measured and used to evaluate how well the routing protocol reflects the physical reality, especially in tactical MANETs where the NLCA often does not match the PHYCON. The discrepancies between the NLCA and the PHYCON could significantly affect the performance in data packet delivery. The data packet delivery failures caused by the network layer connectivity being out of synchronization with the physical connectivity have not, to our best knowledge, been discussed so far in the literature.

Although in this paper we focused on the OLSR protocol, the NLCA metric can be readily applied to other proactive routing protocols because the routable destinations are always available from the routing table. In essence, the NLCA is a network layer measurement of the connectivity of a node to other nodes in the network, so it can be extended to all on-demand and hybrid routing protocols, as long as the calculation for NLCA is properly defined for the protocol. For example, in on-demand routing we may utilize cached routing entries as a measurement of the NLCA.

In tactical MANETs we often desire complete and up-to-date SA (situational awareness) information of the entire network on each node, which is usually provided by an effective SA dissemination scheme, see Li et al. (2014) and Li, Salmanian and Brown (2015) for examples. Such SA dissemination processes can be augmented to also provide multi-hop connectivity information required in the NLCA calculation at each node. This is an alternative way to obtain the NLCA (as an ancillary outcome of the existing SA dissemination process), with the benefit that it is independent of the routing protocol category (proactive, on-demand or hybrid). On the other hand, the NLCA can be used as an independent metric at the network layer to audit and/or verify SA information established in other layers.

Although we implement the NLCA metric for OLSR on the EXata platform in this paper, the idea and methods are platform independent. It is not difficult to extend our implementation of the NLCA metric and PHYCON calculation to other modelling and simulation platforms, such as the information age combat model (IACM) introduced by Cares (2004).

In future work, we are considering the application of the NLCA metric to other proactive and on-demand routing protocols. The PHYCON calculation and the enhanced RPGM model implemented in this paper provide good frameworks for further research in the investigation on tactical MANETs.

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We propose a new local networking metric, the network layer connectivity awareness (NLCA), to dynamically characterize the connectivity status at the network layer of mobile ad hoc networks (MANETs). The NLCA is a local view of routable destinations provided by a designated routing protocol, which may differ from the real-time physical layer connectivity (PHYCON), defined as destinations that can be reached by local nodes via (multi-hop) radio links. Such discrepancy can cause packet delivery failure because a route may no longer be available at physical layer. We present a simulation method to obtain the real-time PHYCON using the breadth-first search algorithm. We apply the NCLA metric to the optimized link state routing (OLSR) protocol in scenarios simulating tactical MANETs, and compare the resulting NLCA with the underlying PHYCON, illustrating the two measurements vary and differ under mobility. The proposed NLCA and investigation technique provide a method for routing performance analysis.