On Improved MANET Network Utilization

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***Abstract*—Mobile ad hoc network (MANET) is a new opportunity for mobile networking using intelligent mobile terminals. However, the widely used shortest path first based routing algorithm leads to various network utilization problems. Mobile terminals have limited power, hence, power saving should be considered when terminals serve as intermediate nodes in MANET. Furthermore, ad hoc routing table calculation is distributed among all network terminals. Therefore, we also need to construct stable paths with longer lifetime in order to reduce the communication overhead introduced by route reconstruction. A less evenly distributed traffic exhausts power on the nodes in the center of the network and leads to shorter path lifetime. Such a network deployment is not fair for the internal nodes. The above problems exist for all routing protocols especially proactive routing protocols based on shortest path first algorithm OLSR. In this paper we study the MANET network utilization in term of load distribution and path lifetime. Our careful simulation results demonstrate that the standard shortest path first algorithm leads to worse load balancing and reduced path lifetime compared to our proposal. When the most unstable network topology is considered, our proposal achieves better network utilization by reducing the peak transmission per node by 15% and the standard deviation of transmission per node by 50%. The average lifetime for established paths is doubled under the most unstable topology.**

I. INTRODUCTION

MANET communications represent an attractive solution to provide broadband and multimedia services among local mobile terminals. To make the upcoming MANET systems fully realizable, mobile terminals need to support new services, and provide performance with adequate Quality of Service (QoS) guarantee. Many research efforts have been reported aiming at MANET performance optimization. Network utilization optimization is also an important research aspect. Unlike wired networks, MANET consists of nodes that have limited power and restricted bandwidth. The special characteristics of MANET nodes cause conflicts of efficiency and fairness in routing optimization. Most of the time, these two objectives cannot be simultaneously achieved. Efficiency focuses on delivery of packages using the fastest and shortest path, while fairness tries to distribute the traffic more uniformly across the MANET. Furthermore, in heterogeneous bit rate environment, fairness should be of more concern because the bandwidth of intermediate nodes along the shortest path can become fully occupied.

In this paper, we study the network utilization in terms of load distribution and path lifetime using the routing optimizations that we previously proposed in [1]. The path lifetime is define as the duration from the moment when the path is established to the moment when the path is considered broken. We already investigated the performance in terms of end-to-end delay, package loss ratio, and the overheads per package introduced by our optimization. The main contributions of this paper are:

- Analysis of various elements in the networking performance and utilization metrics;
- Explanation of the network utilization metrics and their relationships;
- Improvement of the load distribution and the peak transmission per node by 15% and the standard deviation of per node transmission by at least 50%;
- Extension of the lifetime for established paths. The path lifetime is even doubled when the network topology is constantly changing.

This paper is organized as follows. Section II lists the background of this research and related MANET optimizations. The various elements in ad hoc networking utilization are analyzed in section III. The section IV explains the relation among various performance metrics and the cross layer design used for optimization. The simulation results are discussed in section V. We finally conclude the discussion in section VI.

II. BACKGROUND AND RELATED WORK

Researchers have been investigating the load balancing optimizations in MANET [2] [3]. However, these efforts purely focused on uniformed or static network topologies. In such networks, the cost of each hop is always static. Some papers even assume the uniformed costs, which means all the links are equal. This is not realistic while considering the characteristics of MANET nodes and real wireless communication links. Other researchers have been working on hop-count optimization [4], [5]. These studies focus on optimizing ad hoc network performance by minimizing the hop count. Our analysis and simulation results presented in this paper show that the above mentioned approaches are, however, not realistic because network utilization, in terms of load distribution and path lifetime, deteriorates when the routing algorithm uses only the shortest path.

Some research efforts have also been investigating the load distribution fairness of wireless networks [6] [7]. In [6], the authors provided a classical mechanism that applied the max-min fairness at the network queue level. The authors of [7] discussed the wireless Access Point (AP) distribution fairness.

However, the proposals in the above papers are not fully applicable to MANET. In MANET, the package drops are more likely to be caused by failure on wireless interface instead of queue congestion. In addition, the access points do not resemble mobile terminals with limited power and radio capacity.

We propose to use Cross Layer (CL) design to optimize network utilization. However, multiple CL designs cause compatibility and interaction problems, as we analyzed in [1]. We proposed an Infrastructure for CL Designs Interaction (ICDI) in [1] to solve the above mentioned problems. This architecture as demonstrated in Figure 1 reduces the complexity of cross-layer designs by providing a standardized interface to access parameters. The cross-layer information is piggybacked at the end of packages and propagated among layers using the layered messaging procedure. Therefore, the proposed cross-layer architecture is backward compatible with the layered architecture.

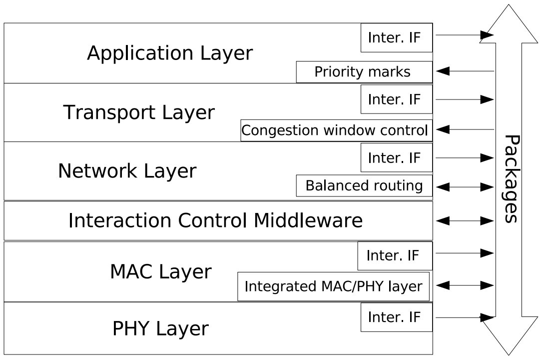

Fig. 1. Infrastructure for CL Designs Interaction (ICDI)

III. AD HOC NETWORK UTILIZATION METRICS

The Mobile Ad hoc networking (MANET) faces similar challenge as wired networks. However, MANETs have some specific properties leading to special QoS requirements. This section explains MANET's generic and special characteristics and their impact on QoS.

A. Load distribution Fairness

In a multi-hop wireless network employing shortest path routing (SP) like OLSR, the topological center of the network is much more communication intensive compared to its edges. This is because the SP algorithm establishes more paths that go through the center. This leads to not only more congestion in the network, but also to increased energy consumption for the nodes on these paths. How balanced the traffic is distributed can be estimated using the standard deviation (SD) of packages transmitted per node in the network. This criterion represents the load distribution better than the peak traffic, because the value represents the effect over time instead of one selected moment. In this paper, we demonstrate that our optimization proposals improve the load balancing measured using standard deviation of package transmission per node.

The Table I lists the differences among wired network, centralized wireless network with stationary Access Point (AP), and MANET in terms of power, mobility, link quality and cause of retransmission. This table indicates load distribution proposals based on wired network like [6], and proposals based on centralized mobile network like [7] are not suitable for MANET. For instance, the proposal of [6] did not consider the high BER and dynamic topology of the wireless mobile network. The authors of [7] proposed solution for optimization on APs, which are stationary powerful centralized control nodes. The authors assume the link quality is perfect without BER and little, if any, retransmission. The intermediate nodes in MANET, however, are less powerful mobile terminals. Furthermore, we need to consider the quality of the links between mobile terminals. If the link quality is bad (higher BER), many retransmissions or even broken paths will occur. In order to solve the above problems, we propose using cross-layer optimization, which can use information from the lower layers (MAC and PHY layers) to determine network and transport layer behavior.

TABLE I
COMPARISON OF NETWORKS

	wired network	centralized wireless network	MANET
node power	indefinite	APs have indefinite power	all nodes with limited power
mobility	stationary	APs are stationary	all nodes are mobile
link quality	no BER	low BER on AP-terminal links	higher BER on all links
retransmission	package drop when full queue	queue drop and some wireless retransmission	significantly more retransmission

B. Fairness and Dynamic BER and Data Rates

Communication channels with higher BER and lower Data Rates are easier to be exhausted. High BER indicates more retransmission. For the same amount of data, high retransmission means high energy consumption. Lower data rate means the capacity of the intermediate nodes is saturated quicker. Therefore, it is possible that the path is broken due to an intermediate node with no radio resources available. In this case, the routing table needs to be recalculated. The above scenario are very undesirable in case of ad hoc networks.

When distribution fairness is not considered in the routing, retransmission and recalculation of routing table will always lead to more overhead. Therefore, the total throughput of the network decreases, even when certain routes and package deliveries are optimized. This paper shows how routing optimization improves the fairness using cross layer designs.

C. Power Consumption

Many papers such as [8] analyzed the power consumption of different radio technologies. The WLAN power consumption is related to link quality, mobility and communication data rate. Normally, the power consumption is in the range of 1500mW for both receiving and transmitting packet as demonstrated in Table II. Another well known fact is that the transmission power consumption is higher on lower data rates, and on links with higher BERs. In [9], the authors present the CPU and memory power consumption of very similar smart phones as those used in [8]. The results show that the power consumption of CPU and memory under various tasks ranges from 20mW to 180mW. It is clear that the power consumptions of the intra-node computation and inter-node communication are not of the same order. Reducing the overall power consumption requires minimization of the communication impact including retransmissions. Considering the fact that transmission is power consuming, the routing algorithm should ideally take the intermediate nodes' power into account when determining routing paths.

TABLE II
COMPUTATION AND COMMUNICATION POWER CONSUMPTIONS OF WIRELESS TERMINALS

	WIFI (AP)	WIFI (ad hoc)	BlueTooth
sending	1500-1600mW	1500-1600mW	550-750mW [8]
receiving	around 1500mW	around 1500mW	450-700mW [8]
computation	20-180mW for various tasks [9]		

In this chapter, we use the peak transmission per node as the indicator for the maximum power consumption for one node. This parameter is defined as the maximum transmission on one node among all the nodes in the network. The node with the peak transmission is obviously the first node to be exhausted. This means the node and all the paths involving this node are not available any longer. By reducing the peak transmission, we prolong the lifetime of the node and all the path along this node.

IV. MANET CROSS-LAYER DESIGN FOR NETWORK UTILIZATION

In this chapter we focus on the tradeoff among hop count, path stability in terms of the path lifetime, and the load balancing in terms of distribution fairness. The above metrics cannot always be optimized simultaneously. The nodes in MANET have some unique characteristics that we described before lead to some preferences and special concerns when we design MANET routing protocols.

- *power consumption awareness*: MANET nodes are mostly small mobile terminals with limited power capacity. This means we cannot allow exhausting certain node's power for inter-connectivity. Power saving is also the most important concern if we aim at long lifetime and availability of the nodes. Normally, the transmission power consumption is significantly bigger compared to computation power consumption. Therefore, we can afford more complicated algorithms that require additional computation per node, but reduce the individual node transmission.
- *link capacity awareness*: MANET nodes have limited bandwidth due to their restricted power capacity and antenna sizes. The intermediate communication load should be distributed evenly in the network regarding the node's transmission capacity. We use the Signal to Noise Ratio (SNR) and collision count to represent link capacity including the effect of interference in the air interface. Higher SNR and less collision lead to better link quality (in terms of BER).

The BER and SNR are used as indicators for link quality ranking. The detail relation between the SNR/collision and BER is not the focus of this research. Please note that the power consumption optimization is per node based. This can obviously lead to increased total transmission activity inside the network, because longer paths that involve more nodes, instead of shortest paths, are used.

A. Relation between Hop-count and Retransmission

Hop-count is simply calculated as the number of intermediate nodes that a successfully delivered package traveled through. The hop count cannot be used to determine optimized path alone. This is because it does not take into account the load distribution and quality of each link. Unfortunately, the above two elements have great impact on the performance of each node in the MANET as well as the overall network performance.

If the hop/link has low reliability, the probability of retransmission is also high. The retransmission is obviously not taken into account by the hop count calculation. Another important characteristic of MANET is that retransmission causes additional interference [10]. The increasing interference, in turn, causes more retransmission. A path with lower hop count but higher total transmission including retransmission is not optimum regarding energy consumption.

B. Cross Layer Optimization

In this chapter, we study the network utilization control with the following three CL designs. The optimization using the CL designs for network performance (end-to-end delay and throughput) is already discussed in [1].

Integrated MAC/PHY Layer (IMPL): The integrated layer provides better information about the wireless link, and consequently provides better information to other CL designs that use MAC layer information. We introduce references to physical layer functions in MAC layer. Therefore, the MAC layer knows information such as SNR and number of packages that fall into noise level. This optimization provides information to the other optimizations. It is registered and activated from the beginning of the simulation.

TCP Congestion (TCPC) optimization: The idea is to use local MAC layer feedback to distinguish package loss caused by network congestion and link errors. The MAC to TCP layer feedback is generated if the retry count in function *RetransmitDATA()* or function *RetransmitRTS()* has exceeded their thresholds. The standard TCP is used in this experiment. On receipt of the MAC layer feedback, the function *slowdown()* in TCP layer does nothing in order to keep the congestion window size. This optimization is registered and activated from the beginning of the simulation. It can be suppressed by Global Load Balancing optimization.

Global Load Balancing (GLB) optimization: This optimization using one-hop neighbor's link information. The general idea is to avoid nodes with lower SNR or more collisions. The local view is represented by the received signal strength and degree of collision. These two parameters can be easily translated into the network density and interference among the neighboring nodes. In the ns-2 simulator, collision can be detected if MAC function *collision()* is called. The number of packages that collide is also available. The local views are piggybacked at end of MAC layer messages and propagated to neighboring nodes. The global view is calculated using the intuitive weighted average method introduced in [11]. Overhearing is not implemented. The OLSR uses the views in their route request procedure. If the local or global view indicates congestion or low SNR, the OLSR sets the willingness to join an Multiple Point Relay (MPR) to WILL_NEVER. Consequently the nodes with stronger SNR and less interference are more likely to join the route. This optimization can be suppressed by the control middleware.

V. VALIDATION AND RESULTS

In order to demonstrate the tradeoff among hop count, load distribution fairness, and path stability, we implement the above three CL optimizations as well as the interaction architecture in the Network Simulator 2 (ns-2) [12] using Optimized Link State Routing (OLSR) [13] as the routing protocols. The OLSR patch for ns-2 is available at [14].

We use the random waypoint mobility model in the ns-2 simulator. In random-based mobility simulation models, the mobile nodes move randomly and freely without any predefined manner. The destination, speed and direction of each node are all chosen randomly and independently of all other nodes. This Markov chain style mobility model is widely used to simulate autonomous movement of mobile terminals. The traffic pattern and node movement are generated using CMU's traffic and scenario generating scripts in ns-2. The results are the arithmetic mean of values from 100 different simulations. The simulation uses the following scenario:

- *mobility model*: random waypoint [15];
- *number of nodes*: 50;
- *area*: 500m × 500m;
- *node speed*: 0 to 20m/s;
- *data sources*: 25 FTP on TCP, and 10 CBR on UDP;
- *test duration*: 600 seconds, pause time is the time in seconds when the mobile nodes are stationary;

We simulate and compare the result from the original OLSR, OLSR with IMPL and TCPC, OLSR with IMPL and GLB, and OLSR with IMPL, TCPC and GLB. Please note that the purpose of this study is not to precisely evaluate the performance of the CL designs, but to demonstrate the relation among hop count, load distribution and path lifetime. Furthermore, the practical control criteria for CL designs are very complicated. The precise relation between QoS requirements and CL control criteria is not the focus of this chapter.

Figure 2 shows that the CL optimizations use higher hop counts for successful package delivery. This is expected for the CL optimizations to select the stable route/hop instead of the shortest path as original OLSR. The effect of the selection mechanism can be clearly observed when the network topology is less stable (when pause time is 0 and 30 seconds, which means that the per hop quality is changing very fast). The CL optimizations are more likely to select links other than shortest path algorithm used by OLSR. When the network topology is more stable (pause time is 300 or 600 seconds), the difference is less obvious. Because we randomize the link quality by dropping packages on the links, the shortest path and CL optimizations still selects different routes when the network is stable. Therefore, our proposal still leads to a little bit long path.

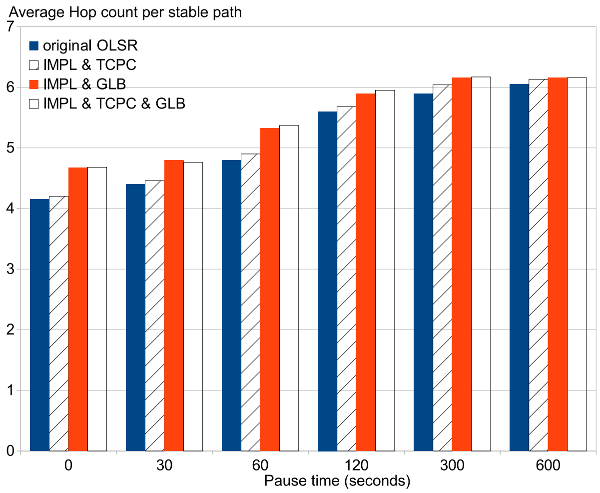

Fig. 2. average hop count per package

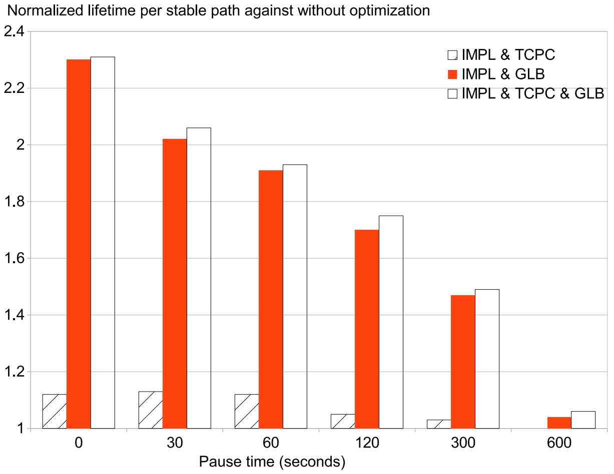

Fig. 3. Normalized lifetime per stable path (original OLSR as 1)

The y-axis of Figure 3 indicates how many times the optimized path lifetime is against the path lifetime of original OLSR. For instance, the path lifetime of our proposal at 0 pause time is 2.3 times longer than that of original OLSR. This is because the movement of the nodes at the network edge is restricted by the edge. Therefore, the distance between the nodes at the edge changes at a smaller range compared to the distance between the nodes in the network center. The nodes at the edge are also less congested. Therefore, the link quality at the network edges is better than that at the network center. Consequently, the routes involving nodes at the network edge exist longer. When the network becomes more stable (pause time is 300 or 600), the improvement is less obvious. This is well expected. When the nodes in the network becomes stationary, the variation of signal strength and link BER is less dynamic. Therefore, the GBL optimization will not reject HELLO messages as it does when the signal strength is fading away (shorter pause time).

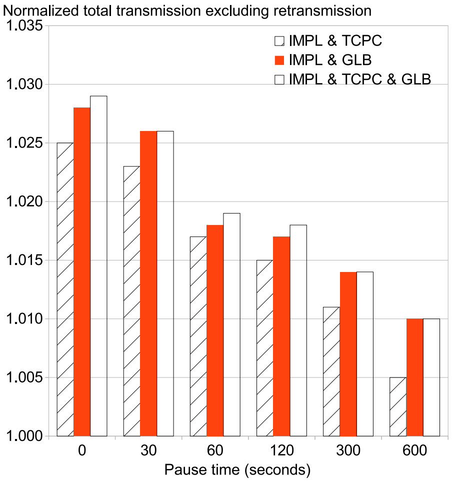

Fig. 4. normalized total transmission amount excluding retransmissions (original OLSR as 1)

Figure 4 illustrates the difference of total transmissions without counting the retransmissions during our simulations. For example, the total transmission using our proposal at pause time 0 is 1.03 times that of original OLSR (3% higher). As shown in the figure, the total transmission amount becomes a little higher when CL optimizations are used. This is a consequence of selecting stable paths against the shortest. When the network is very unstable (pause time is 0 or 30 seconds), the CL optimizations cause 2 to 3 percent more transmissions. However, the transmission count is only on successful delivery. When the retransmissions caused by the broken paths without CL optimization are also counted, the difference is as less as 1% to 1.5%. When the network becomes stable (pause time is 300 and 600 seconds), the difference is less than one percent.

Figure 5 demonstrates the standard deviation of transmission per node. SD value of 0 indicates optimal load balancing, which means all the nodes have the same amount of transmissions. First of all, when the nodes are less mobile (longer pause time), the deviation is bigger. This is because the nodes are more likely to stay close to their starting position. Therefore, the route is more stable and the constructed route is less likely to change. The nodes in the center are naturally better candidates for intermediate nodes. When the network topology is constantly changing (pause time is 0), the positions of nodes are not constant. More nodes are likely to be selected as intermediate nodes. The GBL optimization reduces the SD by at least 50%. This is achieved by pushing the traffic towards the less congested network edge.

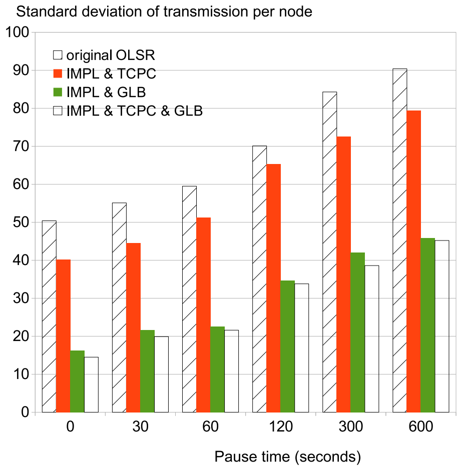

Fig. 5. standard deviation of traffic per node

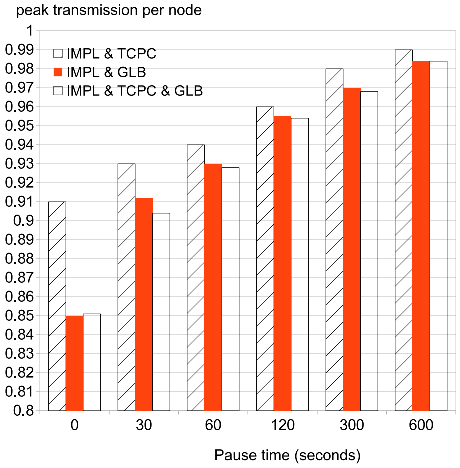

Fig. 6. normalized peak traffic per node (original OLSR as 1)

Figure 6 shows that the peak traffic (maximum transmissions) for one node is reduced when CL optimizations are applied. This is because when a node is busy, collision is more likely to happen. Therefore, the quality ranking of the link is reduced. In the future, the routes involving this node are less likely to be selected. Consequently, the packages use other routes that are less congested. The result indicates that the load and the power consumption are more evenly distributed among all the nodes. The lifetime of the most used node and all the paths involving this node is prolonged. For example, when the network topology is constantly changing (pause time is 0), the peak transmission is 15% lower. Assuming that the data rate is the same as studied in [8], we can estimate that the total transmission power saved in the 600 seconds simulation is about 15% of 1500mW for 600 seconds, which is 135 Joule (watt second).

We observe a tradeoff between the stable path lifetime and the hop count for all the pause time configurations. When node mobility is higher (shorter pause time), the lifetime of the links decreases, forcing the CL optimizations to choose stable but longer paths with a relatively longer lifetime. The average hop count of the stable paths under higher mobility becomes smaller than that under lower mobility. All these performance metrics cannot be optimized at the same time. Longer hop counts caused by GBL optimization also lead to longer lifetime of stable paths. The route lifetime-hop count tradeoff is also expected by our proposed optimization algorithm. The realistic implication of the tradeoff must be studied per circumstance. The simulation configuration is considered high-density with 50 nodes within 500 by 500 meters area. The high density of nodes leads to generally more connectivity. Therefore, the differences of the hop-count and the path lifetime are expected to be smaller than low density network setup.

Obviously, the inherit weakness of OLSR such as neglecting of link quality leads to shorter path lifetime. Shorter path lifetime leads to more end-to-end retransmissions. Therefore, even when the optimizations may choose path that is 20% longer, the total transmission committed is only 3% more than standard OLSR. Maintaining path is more power saving than retransmission as demonstrated in Table II.

VI. CONCLUSION AND FUTURE WORK

The CL optimizations that try to select stable route instead of shortest path lead to increased hop counts and total transmission activity in the network. However, this mechanism increases the total throughput by reducing retransmissions. Furthermore, the CL optimizations distribute the packages more evenly. Although the total amount of transmissions is increased, the maximum transmission effort per node is reduced. Therefore, pressure on the power of a single node is reduced. The above demonstrates that the CL optimizations achieve load distribution fairness in a realistic ad hoc network setup by reducing the peak traffic by more than 15% and standard deviation of transmission per node by 50%. This concludes that the CL optimizations perform better in energy consumption in term of fairness than shortest path algorithm. Also, the average lifetime of established paths can be doubled when the network is unstable. Therefore, the overhead of routing table re-computation is also reduced. Different routing protocols are suitable for different use cases. Our simulation results show that when the network topology becomes more stable, the effect of our optimization decreases. In a realistic environment, the selection of optimization must also consider the detail requirement, such as which aspect of QoS has higher priority than others.

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