Multiple Metrics in MANET with End-to-End QoS Support for Unicast and Multicast Traffic *

Evgeny Khorov Alexander Safonov

Abstract

The paper proposes an approach of using multiple metrics in a wireless multihop network, when one of the metrics called *optimizable* reflects consuming network resources, and other metrics called *restrictive* reflect traffic QoS requirements. Compared to popular Hop Count and Air Time Link metrics, a set of metrics is proposed, increasing the network capacity measured as the number of unicast voice calls with tolerable quality. The metrics are further used in a proposed multicast tree construction algorithm.

1 Introduction

In both wired and wireless networks, a well-known problem of routing has received a lot of attention from academia and standardization bodies. Whatever route criterion a routing protocol implies, an optimizable function called *link metric* is used to weight the links in the network graph and ultimately choose the best route between the source and destination nodes. The criterion usually represents the amount of network resources consumed to deliver a packet.

Quality of Service (QoS) requirements imposed by many applications make the problem more complicated. To satisfy the applications, the route criterion reflecting consuming network resources is amended by the list of QoS restrictions. For example, three parameters determine the quality of voice received through a network: the average packet delivery time, the jitter, i.e. the variation of the delivery time, and the packet delivery ratio. International Telecommunication Union (ITU) recommends an empirically obtained formula for so-called R-factor mapping a combination of these parameters to a perceptional voice quality [1]. So, R-factor determines the boundary values of them which shall not be crossed for a chosen voice quality.

In this paper, we propose an approach of using multiple metrics simultaneously, with one of the metrics which we call *optimizable*, reflecting consuming network resources, and other metrics which we call *restrictive*, reflecting QoS requirements. If a route length crosses a threshold in at least one of the restrictive metrics, the route shall not be chosen for packet delivery, to escape network

*The final version was published in Springer LNCS. Khorov Evgeny, Safonov Alexander. Multiple metrics in MANET with end - to - end QoS support for unicast and multicast traffic . //Lecture Notes in Computer Science, Vol. 6235, p. 251-262, Springer, 2010

resources waste. So, the best route is chosen in an optimizable metric, in the class of routes allowed by restrictive metrics. The approach is applicable for both unicast and multicast traffic, as shown in the paper.

The rest of the paper is organized as follows. In Section 2, we introduce terminology used in the paper and define QoS routing problem formally. Section 3 overviews the simplest and thus popular metrics for wireless networks. A family of metrics is proposed in Section 4, which may be used as optimizable and/or restrictive. In Section 5, we compare proposed and overviewed metrics with a simulation model. Section 6 proposes an algorithm to construct a multicast tree, using multiple metrics, and estimates the algorithm complexity.

2 Preliminaries

The efficiency criterion to compare various routing protocols may be stated, in general, as the total value of packets delivered during some time interval: a protocol providing bigger total value is more efficient. The value of a delivered packet depends on type q of the packet, the amount of consumed network resources, and the end-to-end packet delivery time or other factors imposed by the Quality of Service (QoS) requirements. It also may be negative, when the packet cannot be delivered with appropriate quality of service, e.g. when the packet delivery time reaches some threshold.

Let W be the current total value of packets already delivered in a network. When a packet p of type q is delivered over route l, W is increased by $\delta W(p, q, l)$. The function opposite in sign to the mathematical expectation of $\delta W(p, q, l)$

$$\omega_q(l) = -E_p[\delta W(p, q, l)] \tag{1}$$

is called *the route metric.* It serves to evaluate the quality of route l for delivering a packet of type q. In a particular case when all packets are of the same type, the route metric is a one-variable function of the route: $\omega_q(l) \equiv \omega(l)$.

When routing a packet, the goal is to find such a route $l_q \in L$ that

$$l_q = \arg_l \left[\min_{l \in L} \{\omega_q(l)\} \right], \tag{2}$$

where L is the set of all possible routes in the network for this packet.

In a network of peers with distributed decision making, the value of the metric of a route is not evaluated directly. Instead, another function is introduced representing the contribution of corresponding links to the route metric in question. This function is called *the link metric.*

The physical interpretation of a link metric is usually clearly connected with the routing efficiency criterion. For example, Airtime Link metric (see Section 3) introduced in IEEE 802.11s standard draft [2] represents the channel occupation time required to transmit a packet over the link, including possible retransmissions. The routing efficiency criterion behind this link metric is the total amount of channel resources consumed by all (re-)transmissions of the packet over the route. As we discuss further, this criterion is in a way general, but not connected with any QoS requirement, so the default routing protocol of IEEE 802.11s uses this single criterion for all packet types.

Aiming at providing in a network several levels of service for packets of different types, one needs to introduce several routing criteria clearly reflecting the corresponding QoS expectations. In general, QoS requirements for packet type q may be written as an k_q-dimensional vector $\overrightarrow{\Omega_q}$ of upper bounds of k_q parameters. To estimate the actual value of each parameter, a corresponding link metric $\omega_q^{(i)}, i = \overline{1, k_q}$, may be used. Further in the paper, we refer to this metrics as to *restrictive*, in contrast to $\omega_q(l)$ which we refer to as *optimizable*. Then, denoting optimizable metric $\omega_q^{(0)}(l) \equiv \omega_q(l)$, routing problem (2) turns to be a bounded problem which may be written as follows:

$$l_q = \arg_l \left[\min_{\substack{l \in L \\ \omega_q^{(i)}(l) \leq \Omega_q^{(i)}, i=\overline{1,k_q}}} \left\{ \omega_q^{(0)}(l) \right\} \right]. \quad (3)$$

The issues of link quality estimation and routing information dissemination, which shall be resolved to find solutions of problems (2) and (3), are out of scope of this paper. So, we consider an abstract proactive link state hop-by-hop routing protocol.

Both problems (2) and (3) are also valid for *multicast* route selection, if we put L be the set of all multicast trees covering the source node and destination nodes, and assume that individual transmissions with the same acknowledgment policy as for unicast traffic are used to deliver multicast packets over the tree. Among various multicast tree construction protocols, the common idea is to build a tree of minimal weight, also known as Steiner tree. Obviously, Steiner tree is the solution of (2). In this paper, we discuss a possible solution of (3).

3 "Classical" link metrics

This section overviews simple and thus popular metrics for multihop wireless networks. The simplest metric is called Hop Count. For any route, the metric value equals the number of links the route consists of. The solution of (2), when Hop Count is used, is the path containing minimal possible number of links. Also, the routing efficiency criterion may be interpreted as the number of nodes involved in the packet delivery process.

Thanks to its simplicity, Hop Count is defined as default metric in numerous routing protocols, e.g. AODV [3], OLSR [4], and ZRP [5]. Though, it is known to choose the worst paths in wireless networks, e.g. see [6]. Hop Count metric does not take into account the fact that links data rate and error rate varies a lot in wireless networks. The result of minimizing the number of nodes on the route is that the longest links with lowest signal to noise ratio, and consequently lowest data rate and longest transmission time, are always used. High collision probability provoked by long transmissions increases the number of retries which, in turn, increases the packet service time contributing to the end-to-end packet delivery time. Simulation results of comparing Hop Count with other metrics discussed in this paper are presented in Section 5.

A link metric which directly accounts for lossy links is called Expected Transmission count (ETX) [6]. The ETX of a route is the sum of the ETX for each link in the route. The metric finds paths with the fewest expected number of (re-)transmissions required to deliver a packet all the way to its destination. ETX is calculated based on statistics of already transmitted packets on each wireless link and is proved to find paths with higher throughput, under assumption that a single rate is used on all the links of the network.

Removing this assumption, IEEE 802.11s standard draft [2] introduces Air Time Link (ATL) metric which contains the expected transmission count as a factor and accounts for multi-rate links:

$$\mu_A(i,j) = \left(O + \frac{P}{r_{ij}}\right)\frac{1}{1-e_{ij}}, \tag{4}$$

where O and P are constants representing channel access overhead and standard packet size respectively, r_{ij} is the link (i,j) data rate, and e_{ij} is the probability of transmission error. The route metric is calculated as the sum of the corresponding link metrics.

The physical meaning of ATL metric is as follows: its value equals the time interval when the channel is busy with transmitting the packet over the link. Routing efficiency criterion is the amount of channel resources consumed by this transmission. Implicit assumption that the channel cost is the same on all links is obviously oversimplified, as a transmission in a multihop wireless network only occupies the channel in some neighborhood around the transmitter. Among the nodes in the network, the number of neighbor nodes varies as well as the number of their transmissions in a time unit. Consequently, the channel cost for a node depends on the number of active nodes in its vicinity. Metrics proposed in this paper does take into account active nodes in a transmitter neighborhood, overperforming ATL metric in terms of a number of criteria, as shown in Section 5.

Although the metrics discussed in this section were developed for unicast routing, they are also used in various multicast routing protocols such as MAODV, MOLSR, ODMRP and others. A multicast tree constructed by any of these protocols is simply the union of corresponding unicast paths to all multicast destinations and it is out of line with problem (2). Still, if any of discussed above metrics is used for proactive unicast routing, e.g. by means of OLSR, a multicast tree of minimal weigh may be constructed over known network graph, which would indeed be the solution of (2).

4 Proposed Metrics

4.1 B (Busy)

As mentioned above, the channel cost in different parts of network varies. To enhance ATL metric by taking this fact into account, one need to consider as the link metric the average *packet service time* on the link instead of the channel busy time. The service time of a packet consists of intervals when the packet is actually (re-)transmitted, that is the channel busy time $\mu_A(i,j)$, and intervals when the node counts down its backoff timer, which total length is $backoff_{ij}$, as illustrated in Fig. 1.

The link metric, which we refer to as B (Busy), may be written as follows:

$$\mu_B(i,j) = E\left[backoff_{ij}\right] + \mu_A(i,j). \tag{5}$$

The route metric value equals the sum of corresponding link metric values. Metric B differs from ATL metric by term $backoff_{ij}$. Some papers, e.g. [7], claim this term to be negligible as backoff slots are very small compared to packet duration time. However, this is only true when a single node in the neighborhood is the transmitter and all backoff slots are of minimal length, or, in Bianchi's analytical model terms, all virtual slots are empty [8]. But in the case when several nodes in the transmission range of each other have packet to transmit, the mean duration of a backoff slot grows and may reach packet duration time. So, $backoff_{ij}$ may be even sufficiently greater than $\mu_A(i,j)$.

The value of link metric (5) is easily estimated by statistical data collected by nodes and requires no additional information exchange between nodes. Denote the moment when packet v is enqueued by $T_v^{enqueue}$, and the moments when its service starts and is completed by T_v^{start} and T_v^{end} respectively, see Fig. 1. If a packet is pushed in an empty queue, its service starts immediately: $T_v^{start} = T_v^{enqueue}$. Otherwise, the packet service starts when the previous packet transmission is over: $T_v^{start} = T_{v-1}^{end}$. The packet service is completed when the an ACK is received or the retry threshold is reached.

4.2 D (Delay)

Let us define as link metric D (Delay) the average packet delay on a transmitter. Then, the route metric calculated as the sum of corresponding link metrics represents the end-to-end packet delivery time.

D consists of packet waiting in the queue and packet service time, as illustrated in Fig. 1. The waiting interval starts when the packet is enqueued and ends when the packet service starts. So, for D we write:

$$\mu_D(i,j) = E[waiting_i] + E[backoff_{ij}] + \mu_A(i,j). \tag{6}$$

Waiting interval length only depends on the transmitter, i, while the second and the third terms in (6) depend on the number of retries and hence on the receiver, j, too. Metric D finds the route with the smallest packet delivery time.

4.3 P (Packet loss ratio)

In wireless networks, packets may be lost due to the following reasons: the retry threshold reached, node buffer overflown, lifetime expired. Let p_{ij} be the the probability that node i finally succeeds in packet transmission to neighbor j.

Assuming that packets are only lost when the retry threshold, R, is reached,

$$p_{ij} = 1 - e_{ij}^{R+1}, \tag{7}$$

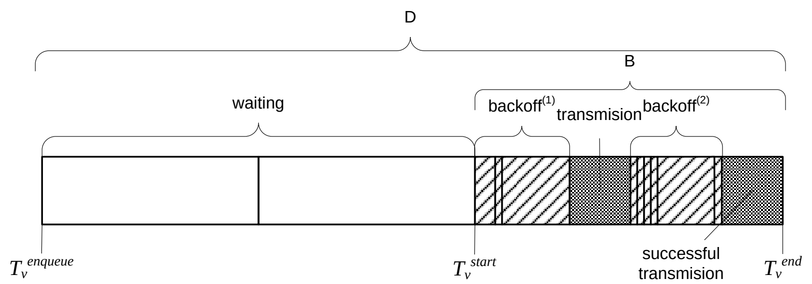

Figure 1: Packet service time, B, and expected packet delay on a node, D

where e_{ij} is the probability of a transmission failure.

If path l consists of, say, two links (i,j) and (j,k), packet delivery ratio over the path equals $p_{ij} \cdot p_{jk}$, i.e. route metric is the product of link metrics, but not the sum. To make it additive, define link metric P as follows:

$$\mu_P(i,j) = -ln(p_{ij}). \tag{8}$$

Metric P chooses a route with the highest packet delivery ratio. However, the metric is in a way selfish and does not take account the amount of consuming network resources. Thus, as shown in Section 5, this metric cannot be used as optimizable.

5 Simulation results

5.1 Simulation setup

To compare the metrics proposed in Section 4 and the metrics overviewed in Section 5, we use simulation tool NS3 [9] with IEEE 802.11s module developed by IITP RAS [11].

Instead of default routing protocol HWMP, we use an abstract link state proactive hop-by-hop routing protocol broadcasting topology info with the refresh interval equal to 1 s.

As traffic source, we use a UDP application which generates packets of size PS. The interval between packets is randomized in $(0.9 \cdot PI, 1.1 \cdot PI)$. The UDP application runs in 2 configurations: “Voice” ($PS = 20$ bytes, $PI = 0.02$ s) and “Data” ($PS = 1024$ bytes, PI is variable).

To analyze proposed metrics we consider two scenarios. In both scenarios, we analyze how voice traffic is delivered via a multihop wireless network. We define the availability of voice service, VA, as the probability that R-factor exceeds 50, according to ITU recommendation [1], and consider VA as the ultimate criterion of routing efficiency.

5.2 Scenario “Circle”

In this scenario, we consider the topology shown in Fig 2. Nodes connected with a line are neighbors and can exchange packets directly.

Other pairs of nodes do not sense transmission of each other.

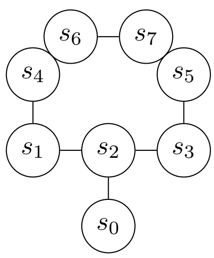

Figure 2: Topology for scenario “Circle”

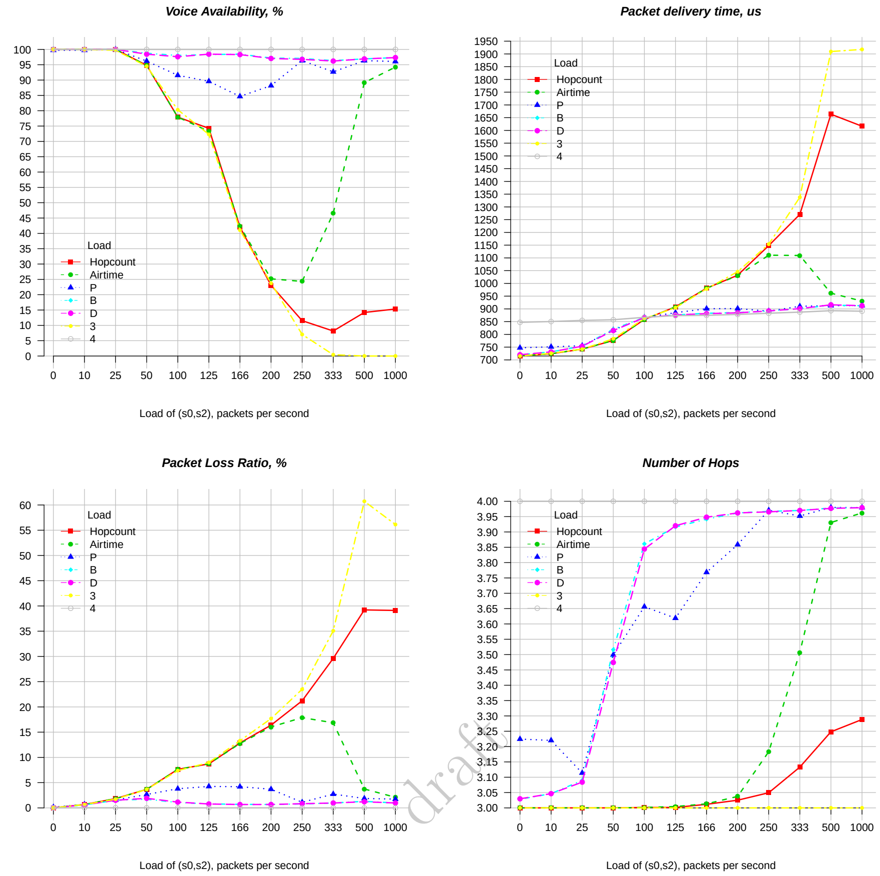

Figure 3: Voice availability, packet delivery time, packet loss ratio and average route length in scenario "Circle"

Application "Data" at node s_0 generates packets destined to node s_2, with access category AC_BE. Another application "Voice" at node s_4 generates packets destined to node s_3. Two routes exist between nodes s_4 and s_3.

In this scenario, we analyze the dependence of VA for "Voice" traffic on "Data" traffic rate. In the results shown in Fig. 3, line "3" corresponds to the case when static 3-hops route s_4, s_1, s_2, s_3 is used, and the line "4" corresponds to the static 4-hops route s_4, s_6, s_7, s_5, s_3. Other lines correspond to the cases when metrics ATL, B, D, and P are used.

To explain the VA results, let us consider the curves of the packet delivery time, packed loss ratio and route length. When the load on link (s_0, s_2) is low, any route gives high voice availability. However, the 3-hop route is preferred because it ensures lower network resources consumption. The collision probability of voice and data packets increases with the load on link (s_0, s_2), and 4-hops route becomes the best choice.

As to Hop Count metric, it always finds the 3-hops route, except for the case when the load on (s_0, s_2) is very high. In this case, the topology control frames often come into collisions, so the chosen path is unstable, switching between

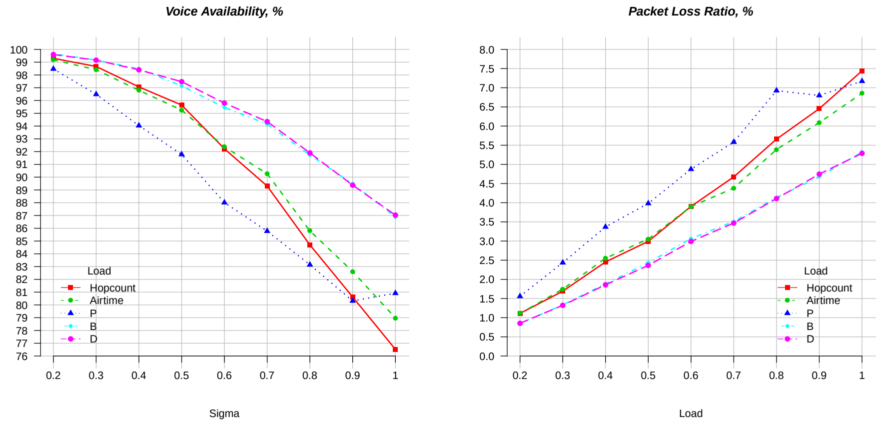

Figure 4: Voice availability, packet loss ratio in scenario "Grid"

3-hops and 4-hops routes from time to time.

By taking the backoff time into account, metrics B and D appear more sensitive to "Data" load growth than ATL, so the 3-hop path switches to 4-hop path just in time, providing better VA. Unlike ATL, these metrics grow with both the number of retries and the average length of a virtual slot, as explained in Section 4. ATL metric only prefers the 4-hops route when (s_0, s_2) load is close to maximum.

B and D metrics show almost the same results because $\mu_D(i, j)$ differs from $\mu_B(i, j)$ by a significant value only if there are packets in the queue of node i during long time interval. It does not happen in this scenario.

5.3 Scenario "Grid"

In this scenario, we consider a network of NxN grid topology. Pairs of source-destination are chosen randomly. Let σ be the network load measured as the average number of "Voice" flows $F = \sigma N^2$.

Voice availability and packet loss ratio for the case when N=4 are shown in Fig. 4. For any σ, B and D metrics gives the voice unavailability about twice lower than ATL.

Let us measure the network capacity as the number of unicast voice calls with tolerable quality. Consider the voice quality as tolerable if VA is greater than a threshold. For a reasonable threshold, say, 90% or 95%, B and D metrics provides higher network capacity than ATL metric by about 30%. D metric behaves slightly better, because it feels queue size and keep off bottlenecks.

Despite P metric is designed to select the routes with lowest packet loss ratio, it provides the worst VA. Metric P is selfish and finds long routes with low transmission error probability. This policy results in high consumption of network resources.

As VA depends on packet delivery ratio, metric P may be used as a restrictive metric. E.g., a route is found by an optimizable metric, say, D, and then is inspected by metric P whether the packet delivery ratio is high enough. If it is not, the route shall not be used for packet delivery, to prevent network resources waste.

6 Metric usage in multicast routing

In this section, we consider the problem of multicast routing from source node s to set of destination nodes DS. A lot of algorithms are proposed in literature to construct multicast trees. The solution of problem (2) (see Section 2) is the tree of minimal weight measured in metric ω_q, if we assume L be the set of all multicast trees covering the source node and destination nodes. The minimal weight tree is known as Steiner tree, and (2) is known as Steiner problem.

We propose to use multiple metrics as discussed in previous sections not only for unicast routing, but also for multicast routing. In this case, problem (3) replaces (2). It differs from Steiner problem by the vector of restrictions, $\Omega_q^{(\cdot)}$, on the tree depth measured in restrictive metrics $\omega_q^{(\cdot)}$, while the tree weight is still measured in optimizable metric $\omega_q^{(0)}$, as in Steiner problem.

Problem (3) may also be defined as follows: find the tree of minimal weight in metric $\omega_q^{(0)}$ in the class of trees which depth in metrics $\omega_q^{(\cdot)}$ does not exceed the corresponding upper bound $\Omega_q^{(\cdot)}$. In other words, when restrictions $\Omega_q^{(\cdot)}$ are weak, problem (3) is reduced to Steiner problem. Consequently, problem (3) is NP-complete, as Steiner problem is known to be NP-complete [10].

Further in this section, we specify problem (3) for the case of voice traffic and propose a heuristic algorithm to construct a tree which is the solution of the defined problem. As we consider voice packets only, for brevity and without loss of generality, we omit index q further in this section.

In Section 5, we show that the decisive restricting parameter of the received voice quality is the end-to-end packet delivery ratio. So, excluding the average packet delivery time and the jitter from consideration, we consider vector $\Omega^{(\cdot)}$ consisting of the only component $\Omega^{(1)} = P_{max}$ which is the upper bound of the end-to-end packet delivery ratio measured by metric P defined in Section 4 and denoted as $\omega^{(1)}$ further.

As the optimizable metric we propose to use metric B which reflects consuming network resources well, as shown in Section 5.

It may happen that no tree satisfies restriction $\Omega^{(1)}$, that is there is at least one destination node $d^* \in DS$ such that $\omega^{(1)}(s, d^*) > P_{max}$. To address this case in our algorithm, we propose to reject packets destined to d^*, which seems to be rational as such packets cannot be delivered to d^* with appropriate QoS anyway. Additionally, such packet drops reduce network resources consumed by the multicast flow.

Further, we propose a heuristic algorithm to solve the defined problem by constructing on the network graph, (V, E), the desired tree, $\mathbf{T} \equiv (V_T, E_T)$. Initially, $V_T = \{s\}$ and $E_T = \emptyset$. Let l_{uv}^T, $l_{uv}^{(0)}$ and $l_{uv}^{(1)}$ be the only path from u to v in the tree $\mathbf{T}$, the shortest path in metric $\omega^{(0)}$ and the shortest path in metric $\omega^{(1)}$ respectively. Let $\widetilde{DS}$ be the set destination nodes not covered by $\mathbf{T}$ yet. Initially, $\widetilde{DS} = DS$.

The tree construction algorithm is the following.

1. By means of Dijkstra's algorithm, find two sets of the shortest paths $l^{(0)}$ and $l^{(1)}$ in metrics $\omega^{(0)}$ and $\omega^{(1)}$ respectively from every node in the network to every node in set $\widetilde{DS}$.

2. For every $d \in \widetilde{DS}$, if $\omega^{(1)}(l_{sd}^{(1)}) > \Omega^{(1)}$, i.e. the length of path $l^{(1)}$ from s to d is above the threshold, remove d from $\widetilde{DS}$.

3. If $\widetilde{DS} = \{\emptyset\}$, the algorithm stops and $\mathbf{T}$ cannot be constructed with necessary QoS restrictions. Otherwise, add routes to the nodes from $\widetilde{DS}$ to $\mathbf{T}$: while $\widetilde{DS} \neq \{\emptyset\}$ do

   (a) choose node $d_{next} \in \widetilde{DS}$ with the longest path from tree $\mathbf{T}$, $l_{\mathbf{T}d_{next}}^{(1)}$.

   $$d_{next} = \arg_d \left[\max_{d \in \widetilde{DS}} \left(\min_{v \in V_T} \left\{ \omega^{(1)}(l_{vd}^{(1)}) \right\} \right) \right], \tag{9}$$

   where v is is the start node in the shortest route from the tree to d, $l_{vd_{next}}^{(1)}$ is the shortest route from v to d.

   (b) let $\Upsilon^{(k)}(\mathbf{T}, d_{next})$ be $\{v \in V_T | \omega^{(1)}(l_{sv}^T \oplus l_{vd_{next}}^{(k)}) \leq \Omega^{(1)}\}$ and $\lambda^{(k)}(\mathbf{T}, d_{next})$ be function

   $$\lambda^{(k)}(\mathbf{T}, d_{next}) = \arg_l \left[\min_{v \in \Upsilon^{(k)}(\mathbf{T}, d_{next})} \left\{ \omega^{(0)}(l_{vd_{next}}^{(k)}) \right\} \right]; \tag{10}$$

   if $\Upsilon^{(0)}(\mathbf{T}, d_{next}) \neq \emptyset$, then route $l = \lambda^{(0)}(\mathbf{T}, d_{next})$, else $l = \lambda^{(1)}(\mathbf{T}, d_{next})$;

   (c) add all the nodes and links of route l to $\mathbf{T}$, and exclude d_{next} and all the nodes of route l_{new} from $\widetilde{DS}$ (if any).

If there is a set $\widetilde{DS}$ of several arguments d that comes to minimization of some function $f(d)$ the expression $\arg_d \min_d \{f(d)\}$ returns a random value of $d \in \widetilde{DS}$.

An upper bound of the running time of this algorithm can be expressed as a function of $|V_T|$ and $|DS|$ using the Big-O notation. The running time of the first step is $O(|V_T|log(|V_T|)|DS|$. The running time of choosing each node d_{next} is $O(|V_T||DS|)$ and it takes $O(|V_T|)$ operations to find the route to d_{next} if we store the value $\omega^{(1)}(l_{sv}^T)$ after adding node v to the tree. So, the running time of the algorithm is $O\left(|V_T|log(|V_T|)|DS| + |V_T||DS| + |V_T|\right) \sim O\left[|DS||V_T|log(|V_T|)\right]$.

The running time of proposed algorithm has polynomial growth with the grow of the network size and can be used in practical application.

7 Conclusions and further investigation

In this paper, we have proposed metrics, B and D, which provide significant growth of network capacity measured in the number of voice calls with tolerable voice quality as compared to simple and thus popular Hop Count or Airtime Link metrics defined as default in numerous routing protocols, as it is proved by simulation results.

We also propose an approach of multiple metrics usage in multihop ad hoc networks with end-to-end QoS support for unicast and multicast traffic. Authors are going to perform extensive simulations to evaluate this approach in the nearest future with NS3 simulation tool [9].

References

[1] ITU-T. Recommendation G.107. The E-Model - A Computational Model In Use In Transmission Planning, 2005

[2] IEEE P802.11s/D4.0. Draft STANDARD for Information Technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment: Mesh Networking, 2009

[3] C. Perkins, E. Belding-Royer, S. Das Ad Hoc On-Demand Distance Vector Routing Protocol, IETF MANET Working Group, 2003 `http://www.ietf.org/rfc/rfc3561.txt`

[4] Philippe Jacquet, Paul Mu"hlethaler, Thomas Clausen, Anis Laouiti, Amir Qayyum, Laurent Viennot: Optimized Link State Routing Protocol Proc. of *IEEE INMIC'01*, pp. 62–68 Lahore, Pakistan, 2001

[5] Zygmunt J. Haas, Marc R. Pearlman, Prince Samar: The Zone Routing Protocol (ZRP) for Ad Hoc Networks. IETF MANET Working Group, 2002 `http://www.ietf.org/proceedings/55/I-D/draft-ietf-manet-zone-zrp-04.txt`

[6] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, Robert Morris: A high-throughput path metric for multi-hop wireless routing, Proc. of *MobiCom '03*, pp. 134–146, USA, 2003

[7] Richard Draves, Jitendra Padhye, Brian Zill: Routing in multi-radio, multi-hop wireless mesh networks. Proc. of *MobiCom '04*, pp. 114-128, USA, 2004

[8] G. Bianchi Performance Analysis of the IEEE 802.11 Distributed Coordination Function. IEEE Journal on Selected Areas in Communications 18(3), 2000, P.535-547

[9] The ns-3 network simulator `http://www.nsnam.org/`

[10] R.M. Karp. Complexity of Computer Computations. Reducibility Among Combinatorial Problems, 1972

[11] Kirill Andreev and Pavel Boyko. Simulation Study of VoIP Performance in IEEE 802.11 Wireless Mesh Networks, In Proc. of *MACOM 2010*, Barcelona, 2010