Novel IoT Applications Enabled by TCNet: Trellis Coded Network

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Abstract: This work presents new results in routing in Wireless Sensor Networks, an important Infrastructure for the Internet of Things architecture, using the new concept of Trellis Coded Network - TCNet. The TCNet is based on the concept of convolutional codes and trellis decoder, that allow routing of data collected by randomly distributed micro sensors in ad hoc networks scenarios. This model uses Mealy Machines or low complexity Finite State Machines network nodes ("XOR" gates and shift registers), eliminating the use of any routing tables enabling the implementation of important IoT applications as Sensor Network Virtualization and in scenarios where clusters of nodes allow covering large areas of interest where the sensors are distributed. The application of TCNet algorithm concepts in cases as VSNs and clustering is facilitated due to the flexibility of TCNet to implement route management, becoming a tool to be adopted by Sensor Infrastructure Providers aiming to deploy, for example, QoS-aware end-to-end services.

1 INTRODUCTION

Routing remains a challenge in today's networks. It is recognized that the major contributing factors are the routing tables growth, constraints in the routers technology and the limitations of today's Internet addressing architecture. Routing tables are populated in routers and indicate the best next hop(s) for each reachable destination along a route.

Considering that Wireless Sensor Networks (WSNs) are an important infrastructure for the Internet of Things (IoT) architecture, the interest in using sensor networks in the same universe as IP networks, although the sensor nodes have limited hardware resources, this work explores an innovative approach based on the concept of a "Trellis Coded Network"- (TCNet), where the foundations were introduced in previous works: (i) "Implementation of QoS-aware routing protocols in WSNs using the TCNet" (Lima and Amazonas 2012), where the network nodes are associated to the states of a low complexity Finite State Machine (FSM) and the links of a route are coded as the transition of states of a convolutional code. The routing discovery corresponds to finding the best path in the convolutional code's trellis; (ii) "A Trellis Coded Networks-based approach to solve the hidden and exposed nodes problems in WSN" (Lima and Amazonas 2014), where it is explained how TCNet innovates the decision making process of the node itself, without the need for signaling messages such as "Route Request", "Route Reply" or the "Request to Send (RTS)" and "Clear to Send (CTS) to solve the hidden node problem that is known to degrade the throughput of ad hoc networks due to collisions, and the exposed node problem that results in poor performance by wasting transmission opportunities.

1.1 Related Work

Although some classic protocols as the Border Gateway Protocol (BGP) (Rekhter et al. 2006), Routing Information Protocol (RIP) (Hendrick, 1988), Ad-hoc On Demand Vector Routing (AODV) (Perkins et al. 2003) and Open Shortest Path First OSPF (Moy, 1988) address the scalability of today's Internet routing system to consider the large number of nodes that may be present in Low-Power and Lossy Networks (LLNs) and IoT applications (IETF

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ROLL 2009), a Working Group formed by the Internet Engineering Task Force (IETF) in charge of standardization and specifying the IP protocol recognizes that factors like the routing tables growth, constraints in routers technology and the limitations of today's Internet addressing architecture have driven the efforts in researching new paradigms. Attempts to adapt the routing protocols of infra-structured networks to cases of ad-hoc networks are often inconsistent to address issues as: frequent changes in topologies, poor link quality, restricted bandwidth, and constraints on energy resources. On the other hand, the ad-hoc and sensor networks tend to proliferate as the number of smart objects-based services on the Internet increase.

After this brief Introduction, Section 2 describes the concept of a “Trellis Coded Network”- (TCNet) to define the routing datagrams generated by each of the nodes network, Section 3 presents the performance of TCNet in terms of latency and energy efficiency, Section 4 describes the application of TCNet to the Sensor Network Virtualization (SNV) and clustering scenarios and Section 5 summarizes the conclusions and future works.

2 TRELLIS CODED NETWORKS

The concept of a “Trellis Coded Network”- (TCNet) changes conventional routing paradigms to enable the development of QoS-aware packet forwarding protocols in WSNs that are used to determine the routing datagrams generated by each of the network’s nodes offering the following advantages that are compatible with the limited resources of WSNs:

- Elimination of routing tables;
- Reduced latency by eliminating the route request (RREQ) and route reply (RReply) signaling packets employed, for example, in AODV;
- Implicit self-recovery mechanism in case of failure.

The model is based on finite automata (Hopcroft and Ulman 1955) or FSMs defined by a "cross" function (k_n / out_n) where a sequence of input symbols $\{k_n\}$ generates a sequence of output codes $\{out_n\}$ as shown in Figure 1. The $k_n(t)$ is the input symbol received at time t and generates the output code $out_n(t)$. It is also assumed that at time t, a transition occurs at the FSM from state i to state j. In TCNet each state represents a network node and the transition state indicates that the frame information must be sent from node i to node j.

It is then possible to generate a specific route along a set of nodes, defined by a desired optimization criterion (latency, packet loss, throughput, cost), by shifting an input sequence $\{k_n\}$ in the FSM of the route’s first node, and informed in the frame as a TCNet label.

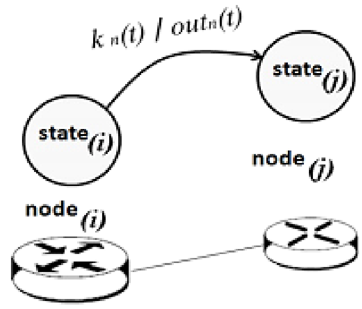


Figure 1: Network node modeled by a state of a FSM.

A network node modeled as a state allows the application of FSM principles in order to exploit the analogy between networks and state diagrams to define paths between nodes. This enables each node to have full knowledge of the network by implementing a paths generator machine (MM) of low complexity ("XOR" gates and shift registers) as shown in Figure 2.

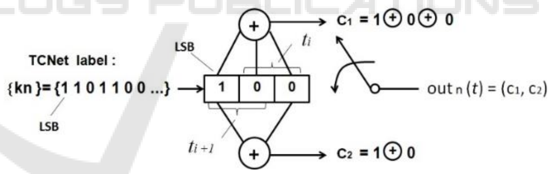


Figure 2: Example of a MM with the input sequence $\{k_n\}$ generating an output sequence $out_n(t) = (c_1,c_2)$.

The TCNet architecture employs the Viterbi algorithm (Proakis and Salehi 2008) proposed in 1967 for decoding convolutional codes based on the trellis diagram to decide a sequence of branches to be followed. The Viterbi algorithm decodes a received sequence by evaluating the distance between the sequence of received source symbols and the weight of the path in the trellis, and identifies the best sequence of branches as the one that provides the minimum distance. This is done by associating each branch with a number called *branch metrics*, and looking for the path whose metrics sum is minimum. This can be accomplished by means of evaluating the *maximum-likelihood* (Gratzer, 1978) and to produce an estimate of the received sequence of symbols.

Figure 3 shows how node-10 recognizes the origin of the emitted sequence to establish a survivor branch (probable partial route). Using the concepts of the Viterbi Algorithm, the node in question analyses the adjacent branches and, using the *Hamming-distance* between the emitted sequence and the respective weights of the branches, decides in favor of the branch with *minimum Hamming-distance* (hard decision-operation), node-00 (Haykin and Moher 2009).

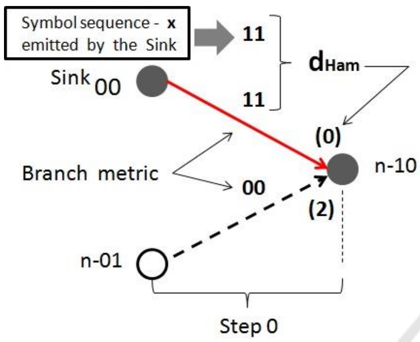


Figure 3: Example of the hard decision taken by node-10 when the sink node-00 emits the sequence $out_n(t)=(c_1, c_2) = (1,1)$.

Using the described procedure, Figure 4 shows the route established by the TCNet label using $\{k_n\} = \{1\ 1\ 0\ 0\}$ and the MM depicted in Figure 2. It can be observed that every node in the network is visited in the order {(10), (11), (01), (00)}, i.e., at the end, the frame returns to the sink node with the information collected from every other node.

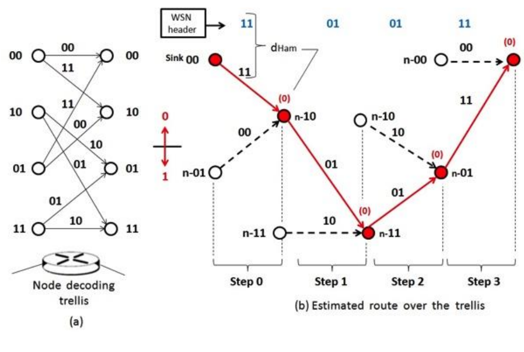


Figure 4: (a) Decoding trellis; (b) Route established by the input sequence $\{k_n\} = \{1\ 1\ 0\ 0\}$ and the MM depicted in Figure 2.

3 TCNet SIMULATION EVALUATION

Consider the WSN scenario illustrated in Figure 5, where the sink node initiates a query through a set of sensor nodes in a predetermined order and also has the function of Access Point to IP infra-structured networks. The sink node initializes a frame loading the WSN header field with the information generated by the MM generator ($out_n(t)=(c_1, c_2)$) and transfers the input sequence ($\{k_n\}$) to the TCNet label field as shown in the Figure 6.

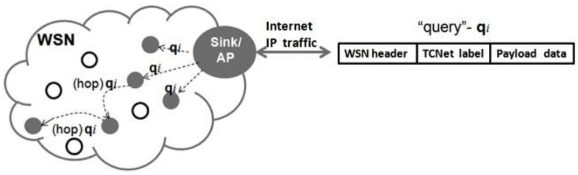


Figure 5: Illustration of a WSN in which the sink node queries a set of sensor nodes. On the right, the TCNet frame is shown.

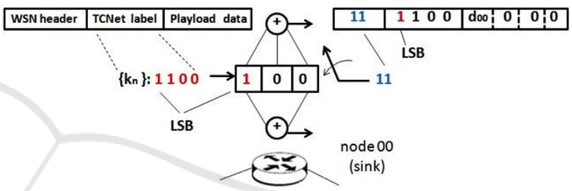


Figure 6: Initialization of the TCNet frame by the sink node: the input sequence $\{k_n\}$ is loaded on the TCNet label field and the output sequence $out_n(t)=(c_1, c_2)$ is loaded on the WSN header field.

The simulation environment used in this work is the OMNeT++ based on C ++ (Varga, 2011) and object oriented. This simulator is widely accepted by the research community for being open software, has been applied to the modeling of network traffic, and as reference for comparisons with other available frameworks.

Tests were done with an 8-node network, where the sink node sends a query with CBR traffic to verify the reachability of the nodes. Figure 7 shows the used node's model, configured by a MM with rate k / n = 1/2 and the respective trellis decoder.

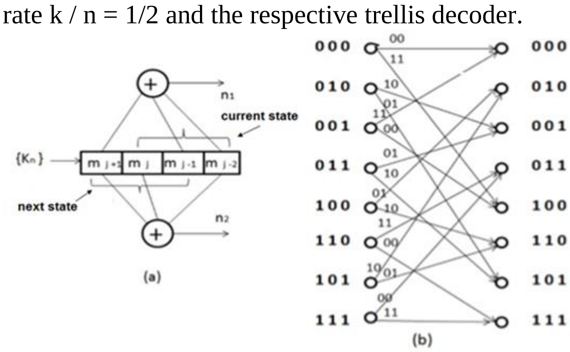


Figure 7: (a) MM with k/n=1/2, resulting output words *(n1, n2);* (b) Trellis diagram corresponding to the MM.

3.1 The TCNet Performance Analysis

The same conditions of parameters and number of nodes of the network were considered in order to perform measurements of latency and energy consumed by the network, as shown in Table 1. The simulations considered a static scenario and the worst-case where the performances for the most physically remote and the most critical nodes of the route were measured.

Table 1: Definition of the simulation scenario.

TCNet	AODV
Topology: 8 nodes randomly positioned in an area (1000m x 1000m) and the sink node initiates communication with the other nodes by queries in the network	Topology: 8 nodes randomly positioned in an area (1000m x 1000m) and the host (0) as source node initiates communication with the other nodes of the network using routes obtained through flooding
Protocol: owner	Protocol: MAC 802.11g
Traffic: CBR with 512-byte packets	Traffic: CBR with 512-byte packets
Simulation time: 1 query	Simulation time: The 1st flooding in the network, with the negotiations (RREQ and RRep) and the ACK confirmation by the host (0)

3.1.1 Latency Efficiency

Figure 8 shows the results of the latency of different nodes of the TCNet network in comparison with a similar route for the AODV case. The latency has been evaluated for the TCNet queries of the most critical nodes (4, 6, 7 and 1), and the same nodes for AODV route establishment mechanism. It can be observed:

- In TCNet the latency increases as the nodes correspond to the last positions of the sequence $k_n(t)$, resulting a longer processing time of the MM during the decision making process of the target node.
- In AODV there is an initial delay in establishing the route and a temporary stabilization of the latency.
- In TCNet the worst-case latency corresponds to 50% of the AODV latency, in the considered scenario of an 8-node network.

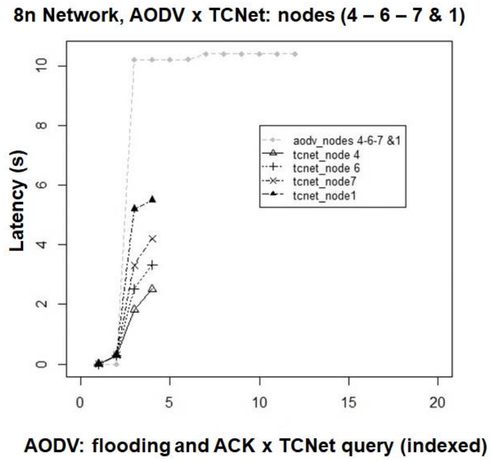


Figure 8: Comparison of TCNet and AODV latency for an 8-node network.

3.1.2 Energy Efficiency

The energy consumed in a WSN is a fundamental parameter due to the limitations of the sources (batteries) that are most often non-replaceable. This work considered the energy consumed by the nodes in the case of the TCNet algorithm, taking into account the power distribution in the following situations: *Transmission (tx), Reception (rx), Processing (proc) and Guard band (gb)*. The following power values were adopted according to the IEEE 802.11b standard:

- *Transmission Power (P_{tx}): 2 mW;*
- *Reception Power (P_{rx}): 1 mW;*
- *Processing Power (P_{proc}): 1 mW;*
- *Guard band (P_{gb}): not considered*

The energy consumed by the node is given by (1), which corresponds to the contribution of the node to the total consumption of the network.

$$\Sigma E_{(n)} = E_{tx} + E_{rx} + E_{proc} + E_{gb} \tag{1}$$

Table 2 shows the energy values for an 8 nodes route considered in the simulation of TCNet network.

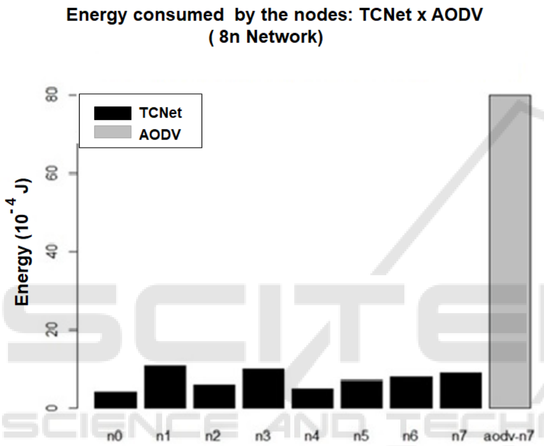
Table 2: Individual contribution to the energy $\Sigma E_{(n)}$ consumed by the nodes of the TCNet network.

$\Sigma E_{(n)}$	Energy (Joule)
$\Sigma E_{(0)}$	4. 10^{-4} J
$\Sigma E_{(4)}$	5. 10^{-4} J
$\Sigma E_{(2)}$	6. 10^{-4} J
$\Sigma E_{(5)}$	7. 10^{-4} J
$\Sigma E_{(6)}$	8. 10^{-4} J
$\Sigma E_{(7)}$	9. 10^{-4} J
$\Sigma E_{(3)}$	10. 10^{-4} J
$\Sigma E_{(1)}$	11. 10^{-4} J

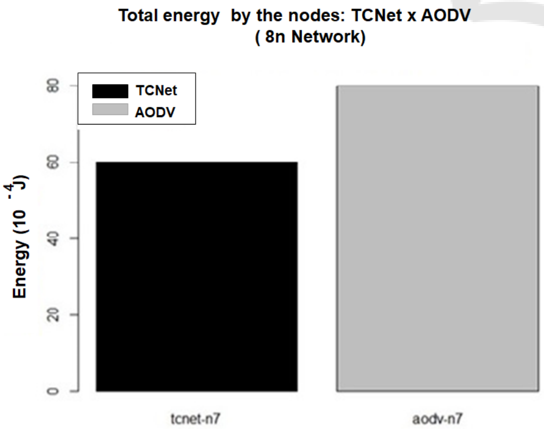
The evaluation of the consumed energy by the AODV considered the total time *(ΣT_{Lat})* taken by the negotiations using the signaling (RREQ, RREP and ACK) to establish the route to the destination node, taking into account that in each AODV event energy consumption occurs in the transmission, reception and processing, respectively given by: E_{tx}, E_{rx} and E_{proc}. Thus the energy consumption for the AODV network is given by (2):

$$ET_{aodv} = \Sigma T_{Lat}\ (P_{tx}+P_{rx}+P_{proc}) \qquad (2)$$

In the comparison of energy consumption, TCNet x AODV, it was considered an 8-node network and a route going through all nodes to reach the most distant node, i.e., node 7. The results are shown in Figures 9 (a) and (b).



(a)



(b)

Figure 9: (a) Energy distributed among TCNet nodes in relation to the energy consumed by the AODV; (b) Comparison between the total energy consumed by the mechanisms of TCNet x AODV.

The total energy consumed by the TCNet corresponds to 75% of the energy consumed by the AODV.

4 APPLICATIONS OF THE TCNet ALGORITHM

4.1 TCNet in Scenarios of Sensor Networks Virtualization

The use of the TCNet algorithm concept in cases of Sensor Network Virtualization (SNV) (Anderson e al 2005), (Chowdhury, 2009) is made easier due to the flexibility of the TCNet algorithm in route management applications.

The TCNet concept becomes a tool that can be adopted by distinct Sensor Infrastructure Providers (SInPs) to establish simultaneous end-to-end services over a same infrastructure as shown in Figure 10.

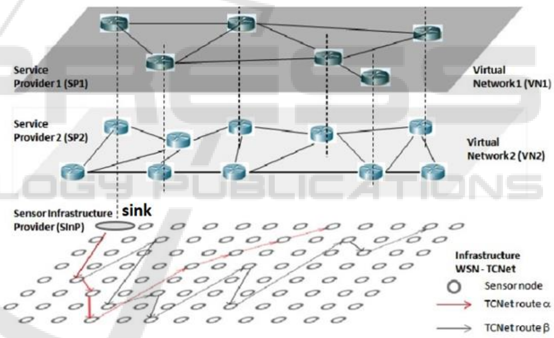


Figure 10: WSN virtualization environment scenario enabled by the TCNet concept where two distinct SInPs establish two simultaneous end-to-end services over the same infrastructure.

The scenario presented in Figures 11 (a), (b) and (c) shows a SNV environment where the sink node manages a heterogeneous set of sensors, over only one infrastructure administered by a (SInP) and controlled by a Gateway Router sensor located in the sink. Figure 11 (c) shows an example of TCNet managing different sets of sensors using queries generated by different sequences corresponding to specific quality requirements for each set of sensors. In this example:

- The humidity sensors are visited by the sequence: k_n *{1 1 0 0 0 0 0 0};*

- The temperature sensors are visited by the sequence: k_n *{1 0 1 0 0 0 0 0};*
- The light sensors are visited by the sequence: k_n *{1 1 1 1 0 0 0 0}.*

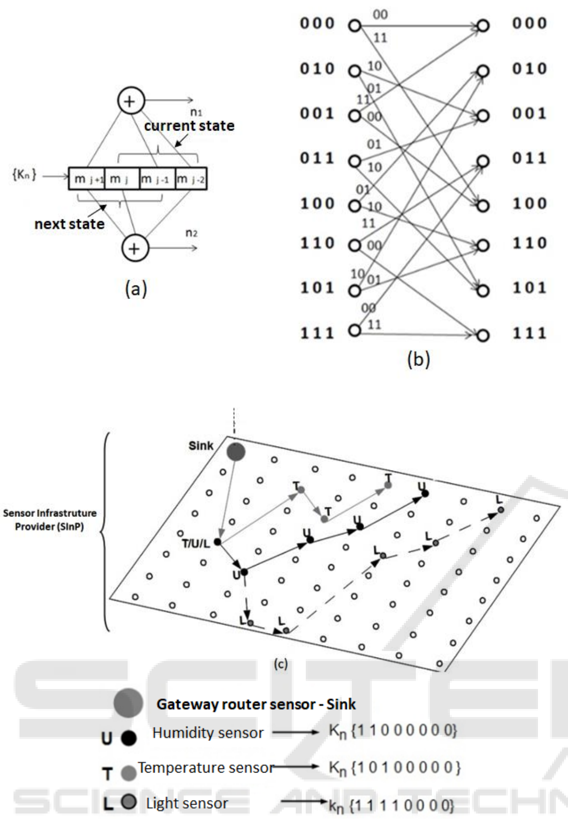


Figure 11: (a) FSM with rate k/n = ½; (b) Trellis diagram related to the FSM; (c) SInP sensors routing sets and sequences related to the respective routes of the sensor sets.

4.2 TCNet in Nodes Clusters Scenarios

Scenarios with large areas of interest to be covered by WSNs suggest the subdivision of these areas into clusters (Murthy and Manoj 2008). The use of TCNet in these cases increases the alternative of connections due to the self-configuration of the trellis, making unnecessary the use of signaling protocols, as would be the case in ad-hoc networks with AODV. Figure 12 shows a scenario with two clusters based on trellis α and β and their respective FSMs, allowing the construction of different routes. Even occurring overlap of neighboring coverage areas, the routes are independent and allows the expansion in order to serve large areas of wireless coverage.

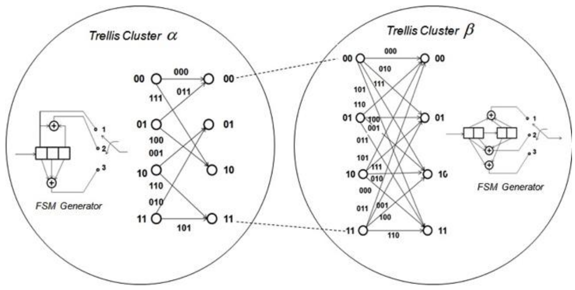


Fig. 12. Clusters α and β have different settings of FSM allowing the construction of independent routes.

The sink nodes, α-00 and β-00, allow the interconnection of the clusters managing the routes after the decision making process has been performed by their respective trellis. The scenario shown in the example of Figure 13 demonstrates data collected from the nodes (α-01 and β-01), belonging to the different clusters, and being transmitted by their respective sinks to be aggregated to the IP traffic by sink β–00 performing its gateway function.

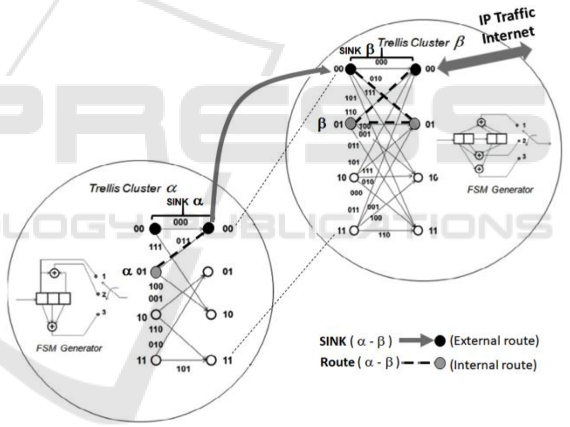


Figure 13: Clusters corresponding to the FSMs **α** and **β** showing a concatenation of the routes between the two clusters.

5 CONCLUSIONS

In this work we have made a review of the TCNet concept that enables the implementation of packets forwarding procedures in limited processing, storage, communication and energy resources networks, as WSNs, without using routing tables. In addition a comparative performance evaluation between the TCNet and the AODV was made showing that the TCNet outperforms the AODV both in terms of worst-case latency and total energy consumption. It has also been demonstrated the potential of TCNet to be used to implement sensor virtualization networks and the management of sensors clusters. These applications are important in the IoT domain and show TCNet as an enabling technology to tackle scalability and to offer different levels of QoS.

The TCNet concept is a powerful tool that can be adopted to face very challenging problems. As future work we will demonstrate how TCNet can be used to implement robust networks with self-recovery properties in the presence of failures.

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