Research Statement

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1 Introduction

Mobile and wireless technologies are becoming part of our daily lives due to luxury of tetherless computing and visionary demands for ubiquitous access to information. As a result, recent years have witnessed a growing interest in the use of wireless ad hoc networks for several daily life applications. Such networks are preferred due to their ease of deployment, maintenance convenient, unattended operation, inexpensive costs and ability to gather data from the environment. Some examples of such applications include environmental monitoring, disaster management, target tracking, remote surveillance, intelligent transportation, border control, building automation, and worker safety control. Due to miniaturization of computing machinery, nodes in such applications are typically small, inexpensive, battery-operated and equipped with radios so that they can relay information to other nodes or get connected to Internet. Other features of the nodes such as sensing, mobility, multi-channels and interaction with the physical world gave raise to various specific types of wireless ad hoc networks including wireless sensor networks (WSNs), mobile ad hoc networks (MANETs), vehicular ad hoc networks (VANETs), wireless mesh networks (WMNs), wireless sensor and actor networks (WSANs) and wireless multimedia sensor network (WMSNs).

These wireless ad hoc networks, however, came with their own challenges which are different than the traditional networks. For instance, due to limited battery life and resources, energy-efficient protocol design is a must. MANETs, VANETs, or WSANs may deploy mobile nodes whose mobility may affect the design of protocols at various layers. In addition to energy conservation and mobility handling, which have been thoroughly studied in the last decade, these networks posed other non-traditional challenges such as self-configuration, self-healing, topology control, node deployment, and energy, security or interference-aware quality of service (QoS) provisioning. Self-configuration, self-healing, and node deployment require effective collaboration among the nodes, yet the approaches should be scalable, low-cost and rapidly applicable. Similarly, QoS provisioning approaches should be lightweight while being able to handle mobility, prevent interference among the nodes and incorporate security without additional overhead.

My research has focused on different aspects of these challenges in several types of wireless ad hoc networks. In the past, I worked on the problems at the network layer of WSNs and proposed several novel protocols that deal with delay-constrained routing, aggregation, relocation and mobility of sink (gateway) nodes [12][16][13][17]. Later, I worked on several projects. Next, I will summarize my current and past research projects.

2 Current Projects and Future Research

I have several ongoing projects as part of my research. While some of the projects have already yielded a number of publications, there are still future issues to be worked on. For the rest, the research is still active in the form of paper submissions under review or under preparation.

2.1 Federating Structurally Damaged Wireless Sensor Networks - NSF

Due to the harsh surroundings and violent nature of the applications for WSNs, the network sometimes suffers a large scale damage that involves many nodes which would create multiple disjoint partitions. We investigate strategies for detecting and recovering from such damage through either the placement of relay nodes or relocation of the existing nodes if they have the ability to do so. The project is currently funded by National Science Foundation for the next three years.

The proposed approach using relay nodes opts to re-establish connectivity using the least number of relays while ensuring certain quality in the formed topology [34]. It assumes that the partitioning is detected and the network topology information is available. Unlike contemporary schemes that form a minimum spanning tree among the isolated segments, the proposed approach establishes a topology that resembles a spider web, for which the segments are situated at the perimeter. We extended the work in [34] to also provide 2-connectivity (i.e., at least 2 node independent paths between any two relays) [33].

The second approach is a distributed one which also handles the detection of the partitioning [41]. The detection of partitioning is based on the idea of not being able to find an alternate route within a certain amount of time. Our approach for recovery on the other hand is the first one which can handle the failures of multiple nodes at the same time using former route information and relocating the nodes to the appropriate positions based on the previous routes. The approach is further extended to work under Zigbee standard [35].

We also collaborated with faculty members from Industrial Engineering for another approach which provides near optimal relocation for the second approach [37][22]. This is based on mixed-integer programming formulation. Since this approach was not scalable and it was not distributed, we developed a new heuristic based on Game Theory. The ability of Game Theory to work with incomplete information has been exploited to propose a distributed approach which can scale better [36].

Currently, we are working on a similar Game Theory based heuristic which can address the relay node placement in a distributed manner. Specifically, the nodes will be placed randomly in the damaged areas and they will cooperate to form a connected network.

2.2 QoS and Security aware Routing for Smart Grid

Under an aging and ineffectual energy distribution system, unprecedented initiatives have recently been instituted in many countries to ameliorate the electric grid with the Smart Grid. As part of these efforts, we focus on the underlying communication architecture of the future Smart Grid and propose to use WMNs for such communication. This project studies QoS-aware routing (i.e., timeliness and reliability) for WMNs considering security as well as dynamic channel switching. We plan to build a prototype WMN using the upcoming IEEE 802.11n and 802.11s standards. An initial study of the analysis and taxonomy of current WMN testbeds has been published [39]. Preliminary study of QoS routing in this project has been done in [40]. In addition, a channel assignment scheme which guarantees connectivity has also been published in [38]. We will be collaborating with Siemens research on the testing of proposed routing approaches in their testbeds.

On the security side, we have been working to assess the security overhead on the QoS performance. To this end, we investigated the performance of homomorphic encryption which is used to provide privacy of the users in the Smart Grid. Specifically, we looked at how homomorphic encryption is performing with respect to hop-by-hop encryption when data aggregation is utilized [31]. Data aggregation refers to the fusion of some user data as the data travels through a network of smart meters.

Currently, we plan to look at the security and QoS performance of HWMP which is used as the routing protocol for 802.11s mesh networks. As part of 802.11s research, we plan to look at network monitoring aspects as well. Such monitoring will be used in the context of the Smart Grid information network.

2.3 Wireless Mesh Networks for Mine Safety

Current safety systems for underground mines are mainly based on leaky feeder-based systems which requires deployment of a leaky feeder all the way up to the slope entry of the mine. This is not only inconvenient and costly but also it does not provide fault-tolerance when certain parts of the leaky-feeder are damaged after major collapses. As an alternative, we propose a mesh-based system based on multi-hop communication of wireless radio routers. Such a system can provide the necessary backbone for safety monitoring devices such as RFID tags, sensors and voice over IP (VoIP) devices to communicate with the ground office.

The proposed underground mesh network will consist of 802.11n routers and run 802.11s to provide the following advantages: First, the deployment will be much easier and less costly (i.e., at least 50% compared to current costs) due to less number of routers required. Second, the system will enable integration of IP-based possibly infrared cameras for safe remote controlling of continuous miners given that the mesh backbone can accommodate more traffic. Third, the mesh network will provide better survivability via its redundant communication architecture in case of failure of some of the devices due to accidents and other reasons. We will provide an optimal deployment plan for the routers which will guarantee k-connectivity within the mesh where $k > 1$. A small prototype has already been tested in the offices using Linux and OpenWRT with 6 IEEE 802.11n routers [20]. We plan to develop and test a prototype of the proposed mesh-network at Southern Illinois University Carbondale using the underground labs of the department of Mining Engineering. Specifically, we would like to test the signal propagation issues in tunnel-like environments and assess its effect on the performance of data throughput and transmission range. The necessary modifications to 802.11s standard will then be investigated.

2.4 Authentication and Trust for Vehicular Ad Hoc Networks

Due to criticality of the exchanged information in VANETs, message authentication without exposing the privacy of vehicles is required. Majority of the current authentication schemes for VANETs depend on public-key cryptography which brings a lot of overhead in terms of delay and also requires infrastructure support for certificate verification. Such support may not be available everywhere until the necessary deployments are done. While symmetric-key based techniques can be more efficient in terms of delay and do not depend on infrastructure support, they introduce significant key maintenance overheads. We surveyed all of these protocols and provided a classification depending on different security features in [30].

Later, by considering the natural group behavior of vehicle communications, we have proposed an efficient and lightweight symmetric-key based authentication scheme for VANETs which is based on group communication [29][28]. Since the groups may be dynamic in VANETs, we form and maintain groups led by a leader vehicle which also handles the key management within the group. In addition to the group key, two other universal symmetric keys are used to provide privacy and non-repudiation. This approach is compared with current IEEE 1609.2 security standard and also one other symmetric-key based protocol based on TESLA. Currently, we are exploring other grouping algorithms and compare their performance in terms of delay under secure communication.

In the future, we plan to work on a trust model for VANETs given that authentication approaches will not be adequate when VANET data from cars are compromised. We will utilize our group-based approach and reputation-based framework from the previous research in developing the trust model.

2.5 Efficient Architectures for Wireless Multimedia Sensor Networks

Given the high cost of processing and communicating the multimedia data in wireless multimedia sensor networks (WMSNs), it is important to reduce possible data redundancy from camera sensors. Therefore, camera sensors should only be actuated when an event is detected within their vicinity. In the meantime, the coverage of the event should not be compromised. In [23], we proposed an architecture for WMSNs where the least number of cameras are actuated by the scalar (i.e., non-camera) sensors to avoid possible redundancy in the multimedia data while still providing the necessary event coverage.

Another issue we explored for WMSNs is multi-perspective coverage of the events [24]. With the reducing cost of camera sensors, a large number of such cameras can be deployed in WMSNs which gives the opportunity to provide event coverage from multiple perspectives. We introduced a new metric which can measure multi-perspective coverage(i.e., k-PC) for a particular region where k refers to the number of perspectives. Using this metric, we first provided an analytical framework for calculation of k-PC of a monitored region for a given WMSN topology. We then proposed a binary programming solution for placing the cameras to provide near-optimal k-PC using the least number of cameras. However, this solution may not always guarantee convergence. For guaranteeing the convergence, we proposed a heuristic which can achieve 100% k-PC with the least camera count [42][43]. We also extended the work in [23] to consider multi-perspective coverage and occlusions when actuating the cameras [7].

Our future plan as part of camera placement for MPC is to consider three dimensional (3-D) environments, in particular, underwater surveillance applications. In such applications, the placement of cameras, their actuation and inter-camera communication will be interesting challenges to tackle given the characteristics of communication underwater. In addition, we plan to investigate camera placement under obstacles.

2.6 Object Classification in Wireless Multimedia Sensor Networks

Wireless Multimedia Sensor Networks (WMSNs) are characterized with large number of resource constrained camera sensors. In remote surveillance applications, such resource constraints necessitate the design of lightweight solutions for traditional problems such as object localization and real-time tracking. In [27], we proposed an energy-efficient object localization scheme for WMSNs. The object localization is performed at individual camera sensors. For that purpose, the approach first extracts the detected object from the frame and finds its boundary using frame differencing. Then, by using them, the location of the object is estimated with the help of camera sensors location information, distance of the object to the camera and camera/frame size properties.

After localizing the detected object, its boundary information is again used to fuzzily classify it at the camera sensors. Then, when a detection occurs, from each one of the camera sensors, instead of raw video data or any frame of the video taken from the area, only the limited information containing location and fuzzy classification of the detected object is transmitted to the sink node to be used in object tracking [26]. We further improved this approach by introducing a reactive approach at the sink node. Specifically, the sink defines rules to act on the detected objects [25]. We targeted a power-plant surveillance application and extended the traditional Event-Condition-Action rules by using fuzzy logic.

Currently, we are working to improve the classification capabilities of the camera sensors using a genetic algorithm. The idea is to do training offline and store the necessary code on the individual cameras for improving classification and recognition accuracy.

3 Past Projects

3.1 Efficient Management of Wireless Sensor and Actor Networks

In addition to resource constrained sensors, resource rich and mobile actor nodes are employed in WSANs. These actors can collect data from the sensors and perform appropriate actions as a result of processing such data. To perform the actions at all parts of the region in a timely manner, the actors should be deployed in such a way that they might be able to communicate with each other and cover the whole monitored area. This requires that the actors should be placed carefully prior to network operation in order to maximize the coverage and maintain the inter-actor connectivity. In [15][5], we proposed a distributed actor deployment algorithm that strives to maximize the coverage of actors without violating the connectivity requirement. The approach applies repelling forces between neighboring actors and from the sensors that sit on the boundaries in order to spread them in the region.

In another work, we focused on sensor-actor data delay in conjunction with actor coverage and proposed an actor placement mechanism which considers the minimum delay from each sensor to an actor. This was formulated as vertex 1-center optimization algorithm [18][14]. To also consider the sensor distribution as part of the actor coverage, we utilized k-minimum independent dominating set problem and determined sensor locations to placed the actors [21][9]. This guaranteed k-hop path from each sensor to actor while maintaining a uniform actor distribution among the sensors. This approach, however, assumed a centralized placement of actors to those locations. Therefore, in another work, we proposed a distributed heuristics based on stable matching problem to assign actors to the desired locations with the minimized movement distance. Stable matching is used between actors and sensor (i.e., cluster-head) locations [19][4].

3.2 Dependable Operation of Mobile Sensor/Actor Networks

Mobility has been introduced to sensor networks through the deployment of movable nodes such as robots/actors. In movable wireless networks, network connectivity among the nodes is a crucial factor in order to relay data to the sink node, exchange data for collaboration and perform data aggregation. However, such connectivity can be lost due to a failure of a node and the network can be partitioned. To handle this connectivity problem, we proposed PADRA [11] to detect possible partitions and then restore the network connectivity through controlled relocation of movable nodes. The idea is to identify whether or not the failure of a node will cause partitioning in advance in a distributed manner. If a partitioning is to occur, PADRA designates a failure handler to initiate the connectivity restoration process. The relocated nodes are chosen based on the connected dominating set of the partition. Eventually a dominatee node is the terminal node to stop the relocation. Another approach, namely DARA, chooses a failure handler based on the number of siblings of the neighbors of the failed nodes [1].

Both DARA and PADRA followed cascaded relocation which was first introduced in our former work [8][32]. In those works, considering two sub-network of actors in WSANs, we proposed a movement mechanism to merge these sub-networks with the least total actor movement distance. As opposed to block movement, which moves the sub-networks as a whole towards each other, we utilized the connected dominating set of each sub-networks and move the nodes from each sub-network until they meet at the middle point. This provided significant movement savings in addition to guaranteeing the connectivity of both sub-networks at the end.

We further extended PADRA to handle multiple node failures [10]. The approach, namely, MDAPRA provided a mutual exclusion mechanism in repositioning the nodes to restore connectivity. DARA was also extended to provide restoration of 2-connectivity when same type of failures happens [3]. Another extension was made to consider application level requirements when selecting the actor to move [2]. This requirement was quantized before the deployment at each node and may change during the network operation.

3.3 Node Deployment in Underwater Acoustic Sensor Networks

Self-deployment of sensor nodes in UWSNs is challenging due to certain characteristics of UWSNs such as 3-D environment, restrictions on node movement and longer delays in communication. Given these characteristics, self-deployment of sensor nodes should not only ensure the necessary coverage but also guarantee the connectivity for data transmission as in the case of terrestrial WSNs. In [6], we proposed a distributed node deployment scheme which can increase the initial network coverage in an iterative basis. Assuming that the nodes are initially deployed at the bottom of the water and can only move in vertical direction in 3-D space, the idea is to relocate the nodes at different depths based on a local agreement in order to reduce the sensing overlaps among the neighboring nodes. The nodes continue to adjust their depths until there is no room for improving their coverage.

In the future, we plan to work on connectivity restoration in UWSNs when a node fails and partition the network. We will adapt our previous approaches to 3-D environment based on vertical movement of sensor nodes. In addition, we will work on modeling of the mobility of the sensor on and under water.

References

[1] Abbasi, A., Akkaya, K., and Younis, M. A distributed connectivity restoration algorithm in wireless sensor and actor networks. In *Proceedings of IEEE International Conference on Local Computer Networks, (LCN'07)* (Dublin, Ireland, Oct. 2007).

[2] Abbasi, A., Baraudi, U., Younis, M., and Akkaya, K. C2am: An algorithm for application-aware movement-assisted recovery in wireless sensor and actor networks. In *Proceedings of IEEE International Conference on Wireless Communications and Mobile Computing (IWCMC'09)* (Leipzig, Germany, June 2009).

[3] Abbasi, A., Younis, M., and Akkaya, K. Movement assisted connectivity restoration in wireless sensor and actor networks. In *IEEE Transactions on Parallel and Distributed Systems* (2010).

[4] Akkaya, K., Guneydas, I., and Bicak, A. Autonomous actor positioning in wireless sensor and actor networks using stable-matching. In *International Journal of Parallel, Emergent and Distributed Systems (IJPEDS)* (2010), vol. 25, pp. 439 – 464.

[5] Akkaya, K., and Janapala, S. Maximizing connected coverage via controlled actor relocation in wireless sensor and actor networks. *Elsevier Computer Networks Journal 52*, 14 (2008), 2779–2796.

[6] Akkaya, K., and Newell, A. Distributed node deployment for maximized connected coverage in underwater acoustic sensor networks. In *Elsevier Computer Communications Journal* (2009), vol. 32, pp. 1233–1244.

[7] Akkaya, K., and Newell, A. Distributed collaborative camera actuation for redundant data elimination in wireless multimedia sensor networks. *Elsevier Ad Hoc Networks* (to appear).

[8] Akkaya, K., and Senel, F. Detecting and connecting disjoint sub-networks in wireless sensor and actor networks. In *Elsevier Ad Hoc Networks Journal* (2009), vol. 7, pp. 1330–1346.

[9] Akkaya, K., Senel, F., and Mclaughlan, B. Clustering of wireless sensor and actor networks based on sensor distribution and connectivity. In *Journal of Parallel and Distributed Computing* (2009), vol. 69, pp. 573–587.

[10] Akkaya, K., Senel, F., Thimmapuram, A., and Uludag, S. Distributed recovery from network partitioning in movable sensor/actor networks via controlled mobility. In *IEEE Transactions on Computers* (2010).

[11] Akkaya, K., Senel, F., Thimmapuram, A., and Uludag, S. Distributed recovery of actor failures in wireless sensor and actor networks. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'08)* (Las Vegas, NV, Sept. 2008).

[12] Akkaya, K., and Younis, M. Energy-aware routing of time-constrained traffic in wireless sensor networks. In *International Journal of Communication Systems* (2004), vol. 17, pp. 663–687.

[13] Akkaya, K., and Younis, M. Sink repositioning for enhanced performance in wireless sensor networks. *Elsevier Computer Networks Journal 49*, 4 (2005), 512–534.

[14] Akkaya, K., and Younis, M. Coverage and latency aware actor placement mechanisms in wireless sensor and actor networks. In *International Journal of Sensor Networks special issue of Coverage Problems in Sensor Networks* (2008).

[15] Akkaya, K., and Younis, M. Coverage-aware and connectivity-constrained actor positioning in wireless sensor and actor networks. In *Proceedings of the 26th IEEE International Performance Computing and Communications Conference (IPCCC 2007)* (April 2007, New Orleans, Louisiana).

[16] Akkaya, K., and Younis, M. Efficient aggregation of delay-constrained data in wireless sensor networks. In *Proceedings of Internet Compatible QoS in Ad Hoc Wireless Networks* (Cairo, Egypt, 2005).

[17] Akkaya, K., and Younis, M. Energy-aware routing to a mobile gateway in wireless sensor networks. In *Proceedings of the IEEE Globecom Wireless Ad Hoc and Sensor Networks Workshop* (Dallas, TX, Nov. 2004).

[18] Akkaya, K., and Younis, M. Cola: A coverage and latency aware actor placement for wireless sensor and actor networks. In *Proceedings of IEEE Vehicular Technology Conference (VTC) 2006* (Montreal, CA, Sept. 2006).

[19] Guneydas, I., Akkaya, K., and Bicak, A. Actor positioning in wireless sensor and actor networks using matching theory. In *Proceedings of WWSAN, in conjunction with ICDCS'09* (Montreal, CA, June 2009).

[20] Imboden, T., and Akkaya, K. Performance evaluation of wireless mesh networks using ieee 802.11s and ieee 802.11n. In *under preparation.*

[21] McLaughlan, B., and Akkaya, K. Coverage-based clustering of wireless sensor and actor networks. In *Proceedings of IEEE International Conference on Pervasive Services (ICPS'07)* (Istanbul, Turkey, July 2007).

[22] Nagilla, P. K., Sisikoglu, E., Sir, M. Y., Root, S., and Akkaya, K. Optimal relocation of nodes to restore connectivity in mobile sensor/actor networks. *under review*.

[23] Newell, A., and Akkaya, K. Actuation of camera sensors for redundant data elimination in wireless multimedia sensor networks. In *IEEE International Conference on Communications (ICC'09)* (Dresden, Germany, June 2009).

[24] Newell, A., Akkaya, K., and Yildiz, E. Providing multi-perspective event coverage in wireless multimedia sensor networks. In *Proceedings of IEEE Local Computer Networks (LCN'10)* (Denver, CO, Oct. 2010).

[25] Oztarak, H., Akkaya, K., and Yazici, A. Active rule processing in wireless visual sensor networks. *ACM Multimedia*, under review.

[26] Oztarak, H., Akkaya, K., and Yazici, A. Efficient tracking of multiple objects in wireless multimedia sensor networks. *Ad Hoc Sensor Wireless Networks*, under review.

[27] Oztarak, H., Akkaya, K., and Yazici, A. Lightweigt object localization with a single camera in wireless multimedia sensor networks. In *Proceedings of IEEE International Conference on GLOBECOM* (Hawaii, USA, Dec. 2009).

[28] Riley, M., Akkaya, K., and Fong, K. Delay-efficient geodynamic group-based authentication in vanets. In *IEEE Local Computer Networks (LCN'10)* (Short paper, Denver, CO, Oct. 2010).

[29] Riley, M., Akkaya, K., and Fong, K. A group-based hybrid authentication scheme for cooperative collision warnings in vanet. *Wiley Security and Communications Network* (to appear).

[30] Riley, M., Akkaya, K., and Fong, K. A survey and classification of authentication schemes for vehicular ad hoc networks. *Wiley Security and Communications Network* (to appear).

[31] Saputro, N., and Akkaya, K. Performance evaluation of smart grid data aggregation via homomorphic encryption. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'12)* (to appear).

[32] Senel, F., Akkaya, K., and Younis, M. An efficient mechanism for establishing connectivity in wireless sensor and actor networks. In *Proceedings of IEEE GLOBECOM* (Washington, DC, Dec. 2007).

[33] Senel, F., Younis, M., and Akkaya, K. Bio-inspired relay node placement heuristics for repairing damaged wireless sensor networks. *Vehicular Technology, IEEE Transactions on 60*, 4 (may 2011), 1835 –1848.

[34] Senel, F., Younis, M., and Akkaya, K. A robust relay node placement heuristic for structurally damaged wireless sensor networks. In *Proceedings of IEEE Local Computer Networks (LCN'09)* (Zurich, Switzerland, Oct. 2009).

[35] Senturk, I. F., Akkaya, K., and Vemulapalli, S. Handling large-scale node failures in mobile sensor/robot networks. *under review*.

[36] Senturk, I. F., Yilmaz, S., and Akkaya, K. Connectivity restoration in reactive sensor networks using game theory. *under review*.

[37] Sir, M., Senturk, I., Sisikoglu, E., and Akkaya, K. An optimization-based approach for connecting partitioned mobile sensor/actuator networks. In *Proceedings of 3rd International Workshop on Wireless Sensor Actuator and Robot Networks (WiSARN) in conjunction with IEEE INFOCOM'11* (Shanghai, China, April 2011).

[38] Uludag, S., and Akkaya, K. Distributed channel assignment in wireless mesh networks with guaranteed connectivity. In *Proceedings of IEEE LCN* (Montreal, Canada, Oct. 2008).

[39] Uludag, S., Imboden, T., and Akkaya, K. A taxonomy and evaluation for developing 802.11-based wireless mesh network testbeds. *Wiley International Journal of Communications System* (to appear).

[40] Uludag, S., Perkovic, L., Kashkanova, A., and Akkaya, K. Quality-of-service provisioning via stochastic path selection under weibullian link delays. In *Proceedings of International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine'07)* (Vancouver, Canada, Aug. 2007).

[41] Vemulapalli, S. Mobility-based route recovery from multiple node failures in movable sensor networks. In *MS Thesis, Southern Illinois University Carbondale* (2009).

[42] Yildiz, E., Akkaya, K., Sisikoglu, E., and Sir, M. An exact algorithm for providing multi-perspective event coverage in wireless multimedia sensor networks. In *Proceedings of IEEE International Conference on Wireless Communications and Mobile Computing (IWCMC'11)* (Istanbul, Turkey, July 2011).

[43] Yildiz, E., Akkaya, K., Sisikoglu, E., Sir, M., and Guneydas, I. Camera deployment for video panorama generation in wireless visual sensor networks. In *Proceedings of International Workshop on Video Panorama in conjunction with IEEE Symposium on Multimedia (ISM'11)* (Dana Point, CA, Dec. 2011).