# Correspondence

## A Survey of Recent Advances in Fuzzy Logic in Telecommunications Networks and New Challenges

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***Abstract*— Fuzzy logic has been successfully deployed in many real-world automatic control systems including subway systems, autofocus cameras, washing machines, automobile transmissions, air-conditioners, industrial robots, aerospace, and autonomous robot navigation. In contrast, the use of fuzzy logic in telecommunication systems and networks is recent and limited. Fundamentally, Zadeh's fuzzy set theory provides a robust mathematical framework for dealing with "real-world" imprecision and nonstatistical uncertainty. Given that the present day complex networks are dynamic, that there is great uncertainty associated with the input traffic and other environmental parameters, that they are subject to unexpected overloads, failures and perturbations, and that they defy accurate analytical modeling, fuzzy logic appears to be a promising approach to address many important aspects of networks. This paper reviews the current research efforts in fuzzy logic-based approaches to queuing, buffer management, distributed access control, load management, routing, call acceptance, policing, congestion mitigation, bandwidth allocation, channel assignment, network management, and quantitative performance evaluation in networks. The review underscores the future potential and promise of fuzzy logic in networks. The paper then presents a list of key research efforts in the areas of fuzzy logic-based algorithms and new hardware and software architectures that are necessary both to address new challenges in networking and to help realize the full potential of fuzzy logic in networks.**

***Index Terms*—Challenges, fuzzy logic, hardware, survey, telecommunications networks.**

### I. Introduction

The discipline of fuzzy logic, fuzzy systems, and fuzzy modeling has witnessed its greatest success in real-world automatic control applications, including subway control, autonomous robot navigation, autofocus cameras, image analysis, and diagnosis systems. Information processing based on fuzzy logic theory requires extensive computation and, hence, the computation time becomes the critical issue. The literature records a number of research efforts by the fuzzy logic community aimed at developing advanced hardware for fast execution of fuzzy logic. In addition, a number of commercial vendors offer a combination of hardware and software for developing fuzzy systems. They include Accel Infotech Spore Pte, Ltd., Adaptive Informations Systems, American NeuraLogix, Aptronix, ByteCraft, Ltd., Fril Systems Ltd., Fujitsu, FuziWare, FuzzySoft AG, Fuzzy Systems Engineering, HyperLogic, Inc., Inform, Metus Systems Group, Modico, Oki Electric, OMRON Corporation, Togai InfraLogic, Inc., Toshiba, TransferTech GmbH, Honeywell IAC, Integrated Systems Inc., SGS-Thomson, Siemens, and others.

Gasos *et al*. [1] describe a fuzzy system for autonomous mobile robots wherein the control variables—velocity and steering wheel angle—are both computed quickly by three modules, all based on fuzzy logic. The system permits maximum velocity and acceleration of 0.6 m/s and 0.4 m/s/s, despite steering wheel angle ranges between $-28^\circ$ and $+28^\circ$, maximum steering wheel turning speed of $8^\circ$/s, and a sampling time of 0.25 s. Akahoshi [2] presents a fuzzy logic controller (FLC) that successfully controls the automatic exposure, focus, and zoom modes of a single lens reflex (SLR) camera. The fuzzy engine delivers inferences in a few milliseconds with two inputs, five labels, two rules, and a membership function that is described as a table using 8-bit grades and 16-point coordinates and the fuzzy inference engine occupies approximately 500 bytes in the program area. Zimmermann [3] describes a research vehicle capable of a top speed of 80 km/h with a built-in knowledge base that renders it completely independent of any communication with outside senders. The vehicle utilizes a four-node transputer net generating a computational power equivalent to 40 MIPS/6 MFLOPS to execute the fuzzy inferences fast and yield a reaction time of under 10 ms. Martinez and Jamshidi [4] describe a fuzzy system for idle speed control in automobiles that produces significant improvement, relative to the open-loop system, and achieves overshoot and settling times of 12% and 1.4 s, respectively. They note that while a fuzzy system that utilizes output and derivative feedback outperforms open-loop, Crisp P, Crisp PD, and Crisp PD control schemes in overshoot performance and settling time, a fuzzy system with only output feedback offers slightly better settling time but worse overshoot performance.

Watanabe [5] notes that while application-specific integrated circuits (ASIC's) have been successful in achieving fast fuzzy inferences, they are expensive, require a significant turnaround time, are inflexible, and are limited in their capabilities. ASIC chips have been utilized in an experimental robot at the Oak Ridge National Laboratory and on a VME bus board developed for the NASA Ames Research Center. However, following the delivery of the ASIC chips, researchers quickly noted mismatches of the chip functionality relative to the objectives of the application project. Lee and Bien [6] note that current computing architectures do not lend themselves to scalability to meet the requirements of a higher capacity FLC. They propose a scalable architecture that permits an easy increase of the capacity of an FLC by merely adding modules and one that utilizes pipelined parallelism for higher performance. Tokunaga [7] describes the FUTURE BOARD—a high-speed hardware board for fast processing of fuzzy set operations. The board consists of exclusive data memory for fuzzy sets, fuzzy data memory, and four fuzzy set processors (FSP's) to concurrently execute four streams of fuzzy operations on 8-bit data. The result is a performance that exceeds ten times that of the SUN-4 workstation. The FSP consists of four 16-bit basic operation units and a microprogram control circuit that operate at 10 MHz. For input/output, the FSP has two input buses and one output bus, each having a width of 32 bits. The FSP exhibits the equivalent processing capacity of 15 times that of a reduced instruction set computer (RISC) processor working at 20 MHz on basic operations on fuzzy sets.

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